Understanding the Field and Frequency Dependence of RF Loss in SRF Cavities

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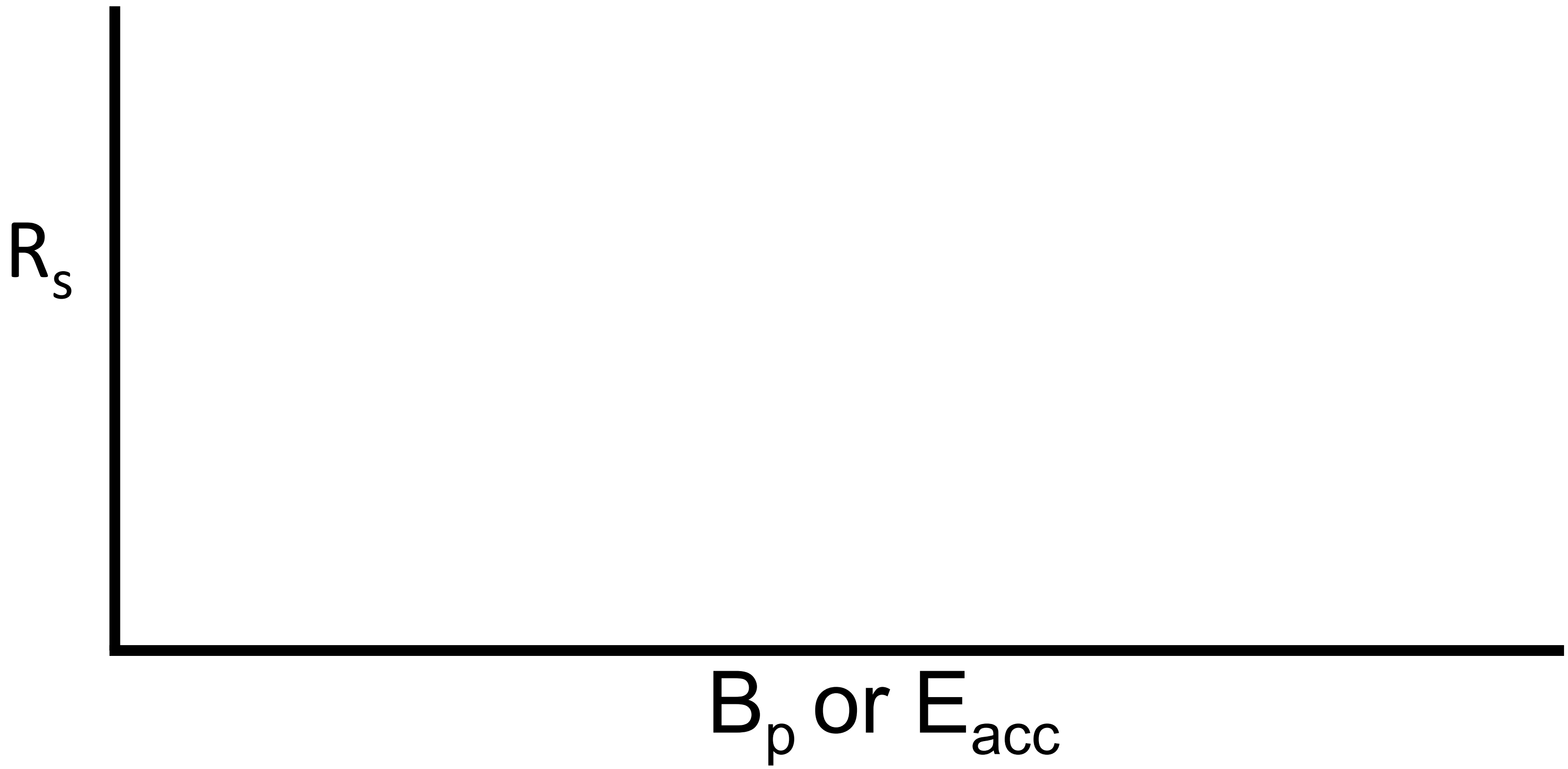
Office of Nuclear Physics under contract DE-AC05-06OR23177

Outline

- RF loss
- Q- Slope or Q-Rise
- What do we know about Q-rise?
- Surface Alloying
- Temperature and Frequency Dependence

Surface Resistance of SRF Cavities



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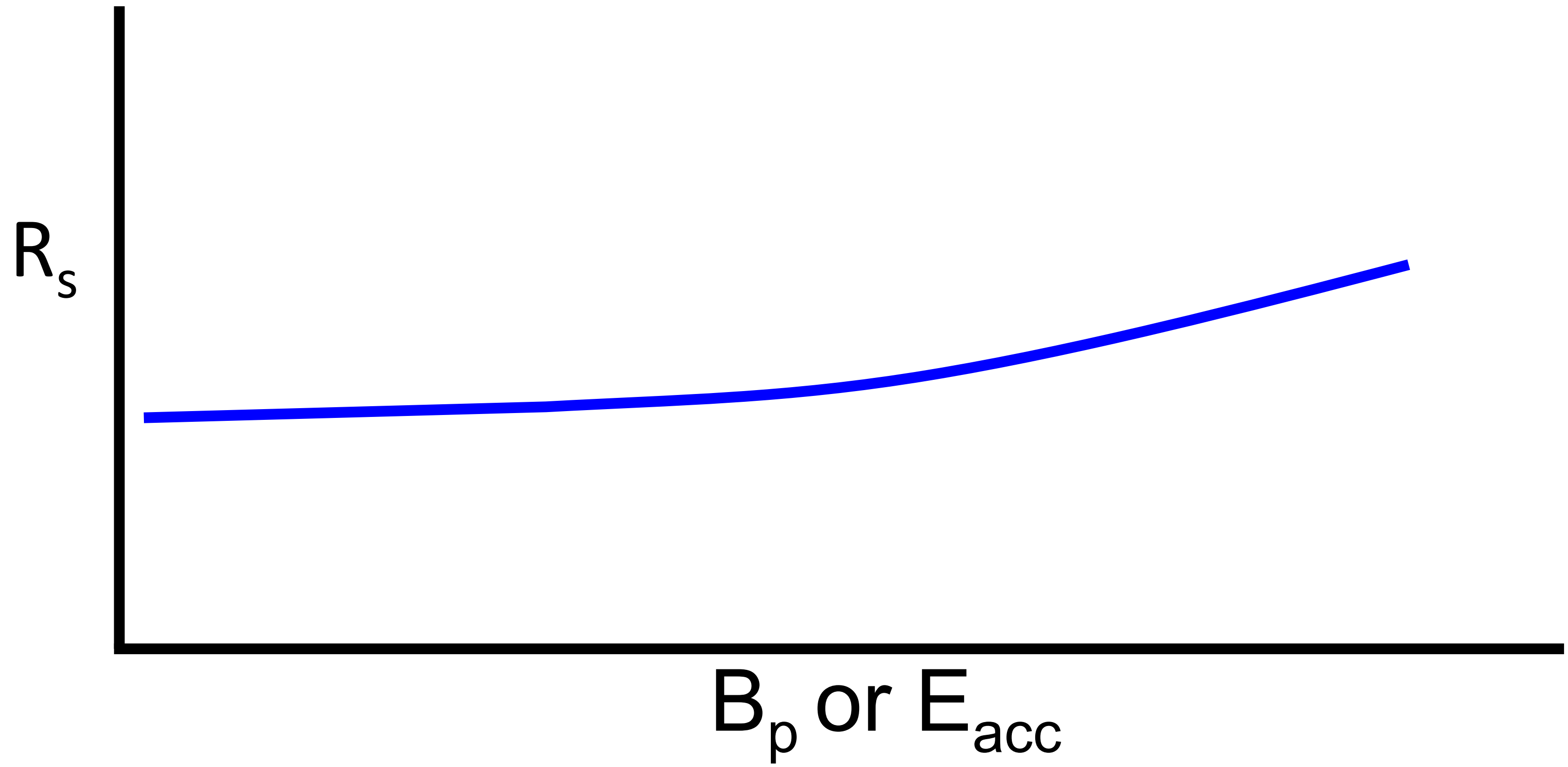

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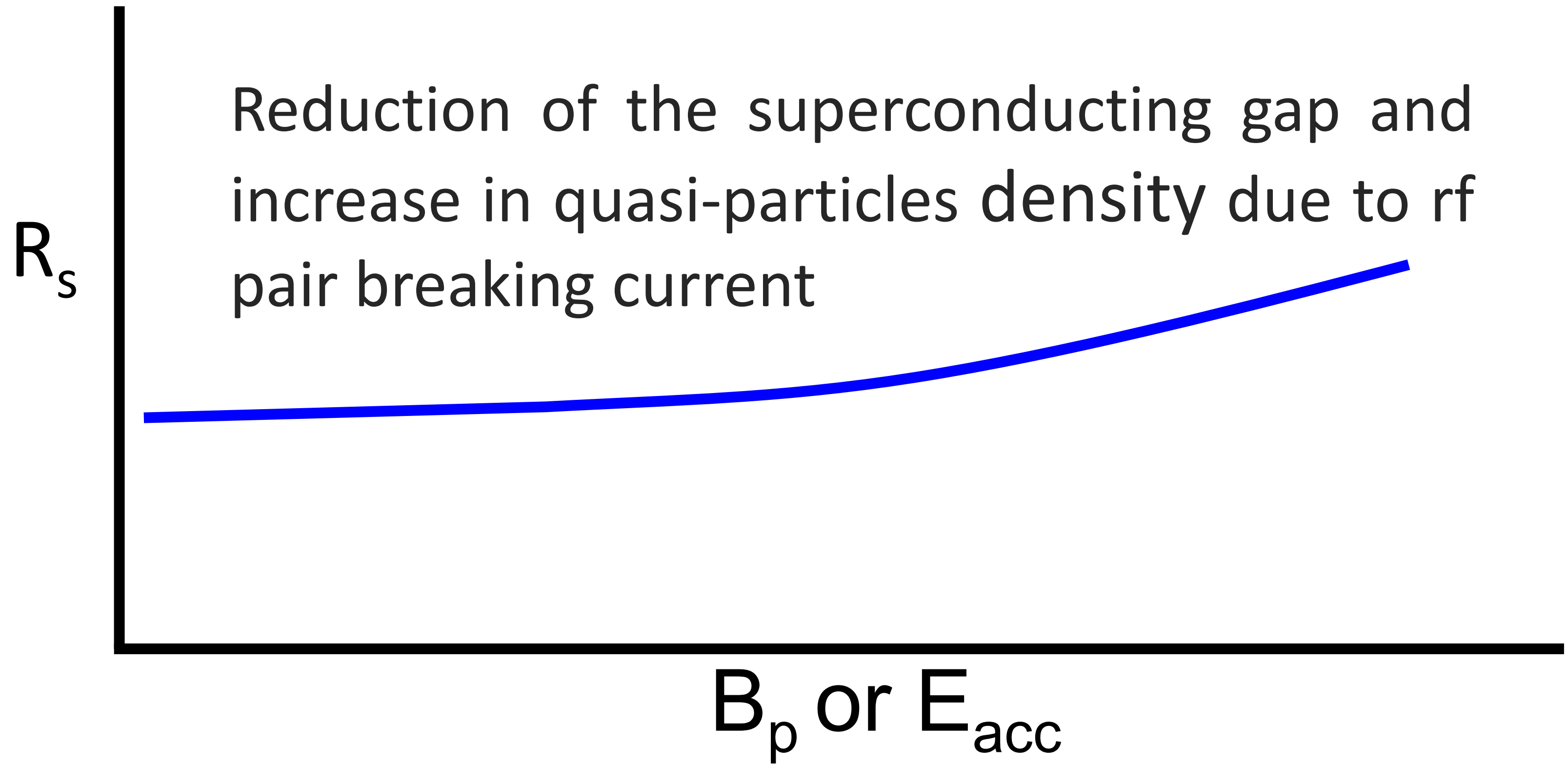

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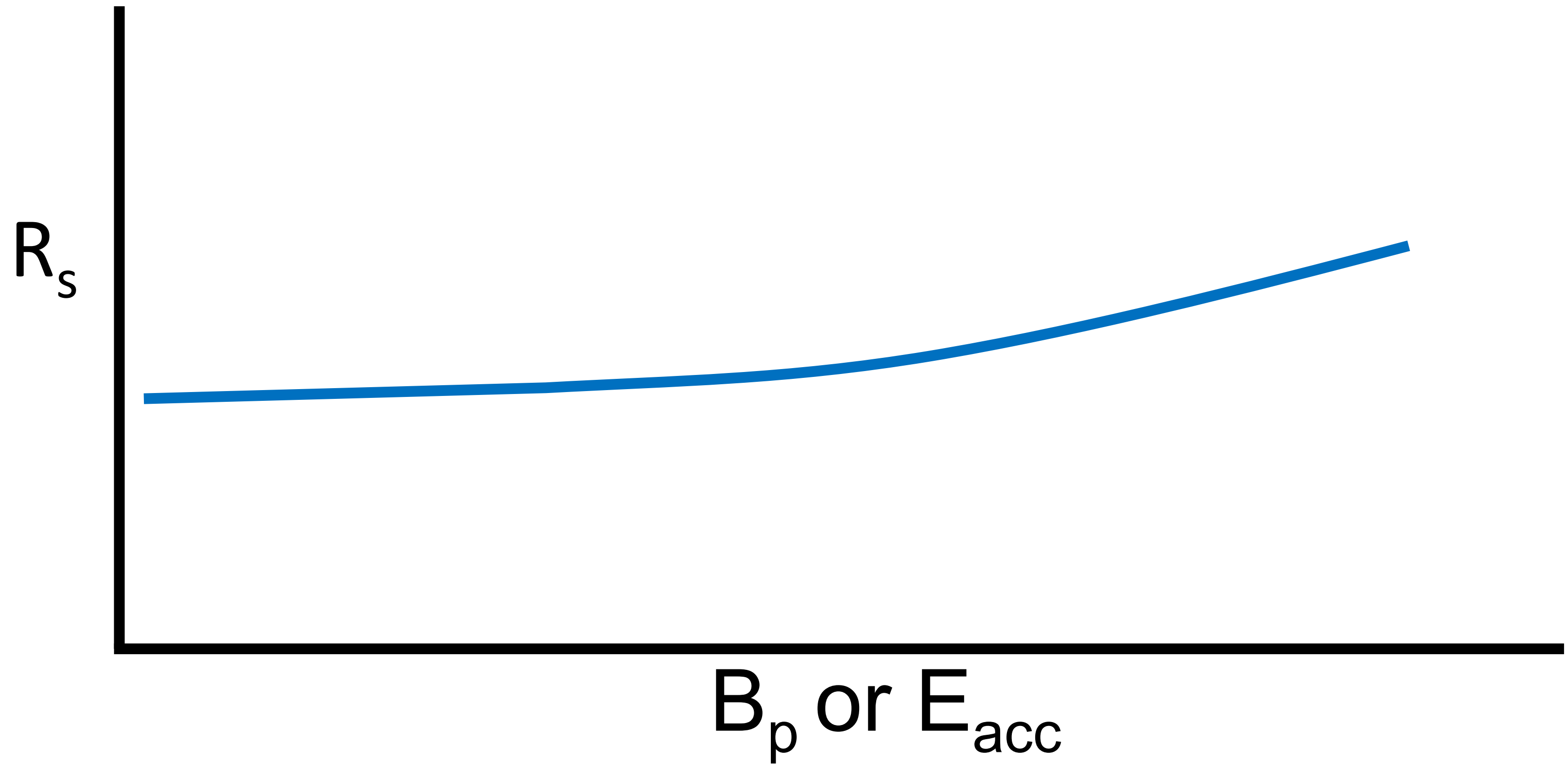
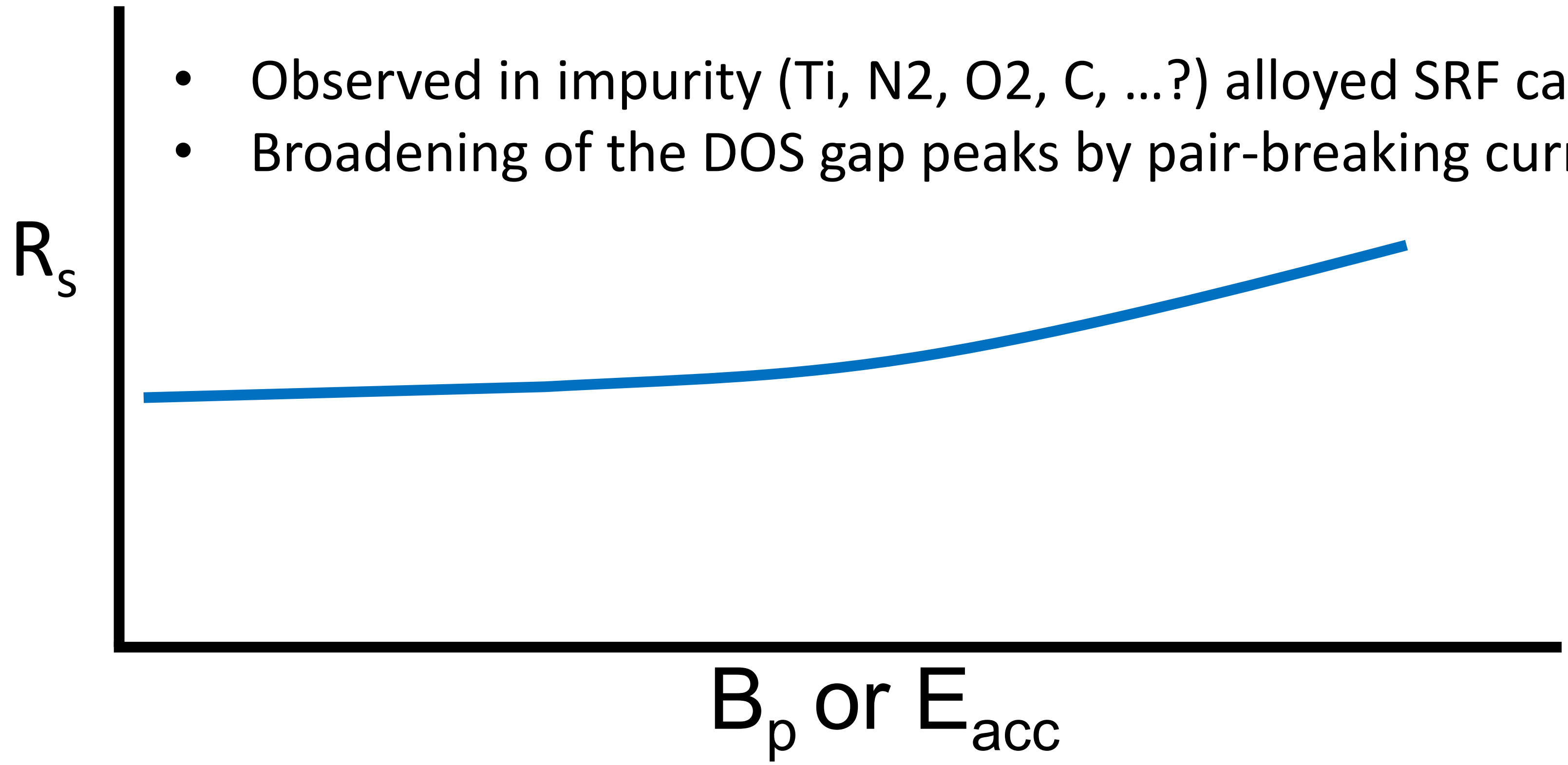


Surface Resistance of SRF Cavities

- Observed in impurity (Ti, N2, O2, C, …?) alloyed SRF cavities
- Broadening of the DOS gap peaks by pair-breaking current



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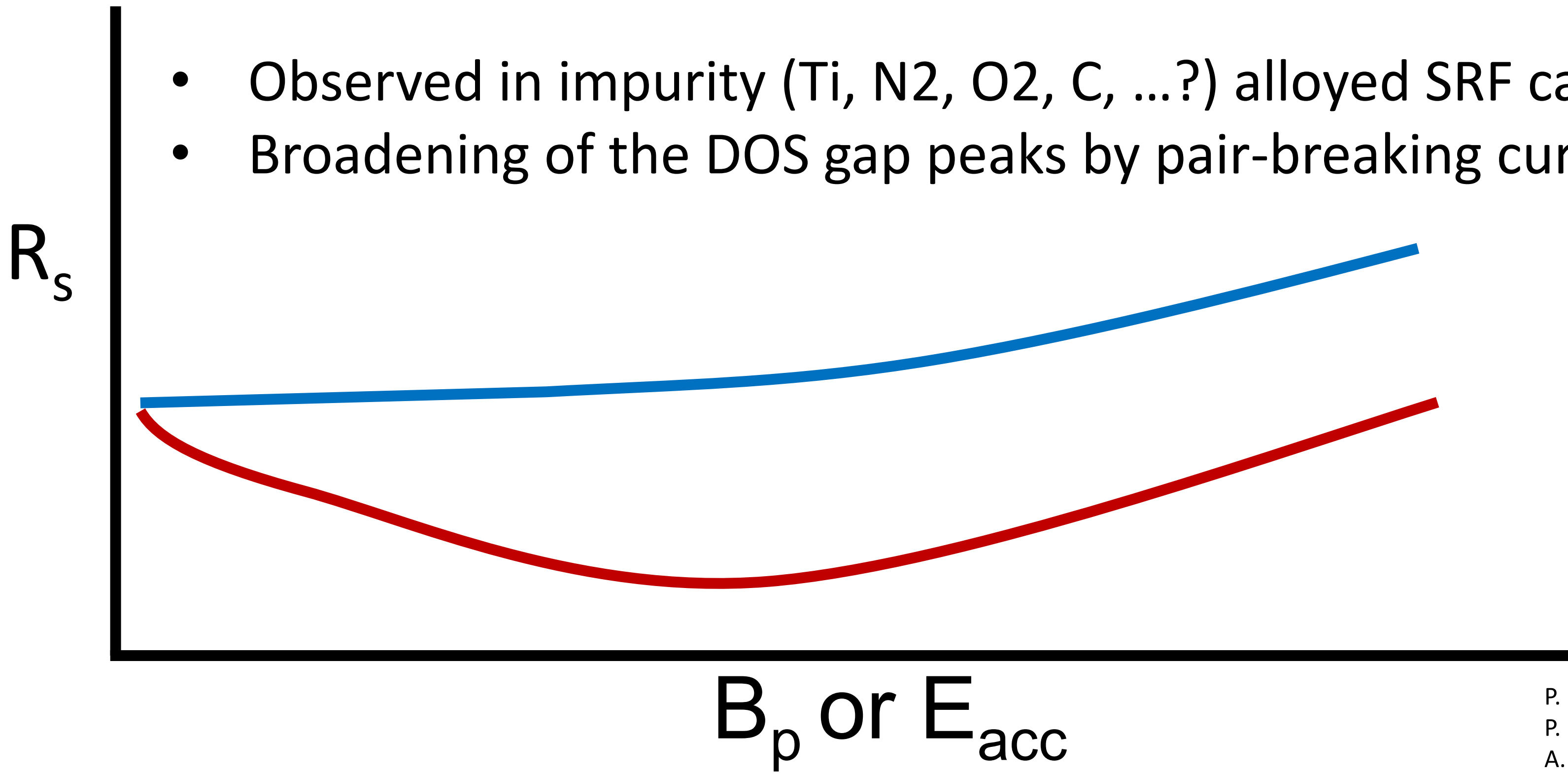
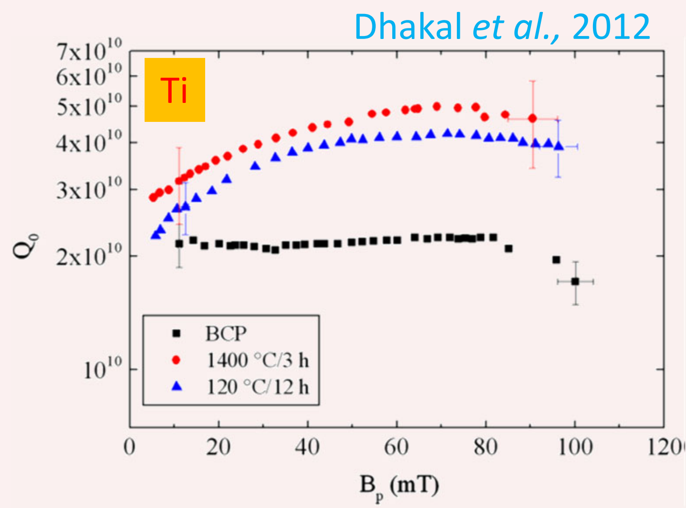
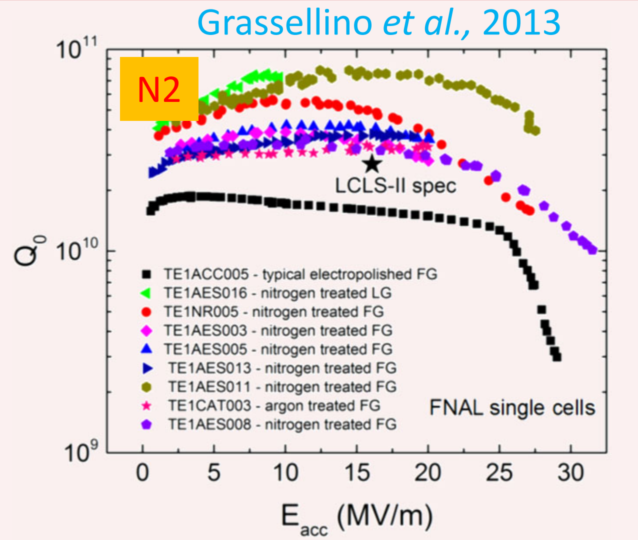


P. Dhakal *et al.*, IPAC (2012)
P. Dhakal *et al.*, PRAB (2013)
A. Grassellino *et al.*, SUST (2013)
A. Gurevich, PRL (2014)

High Q_0 Recipe





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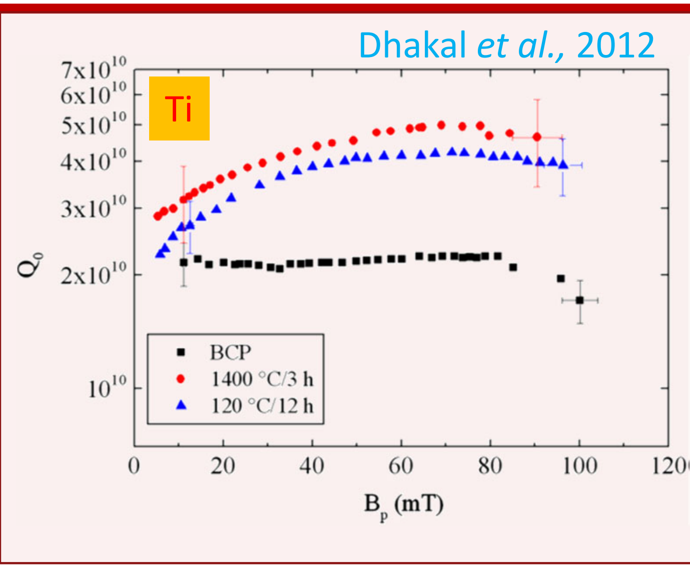

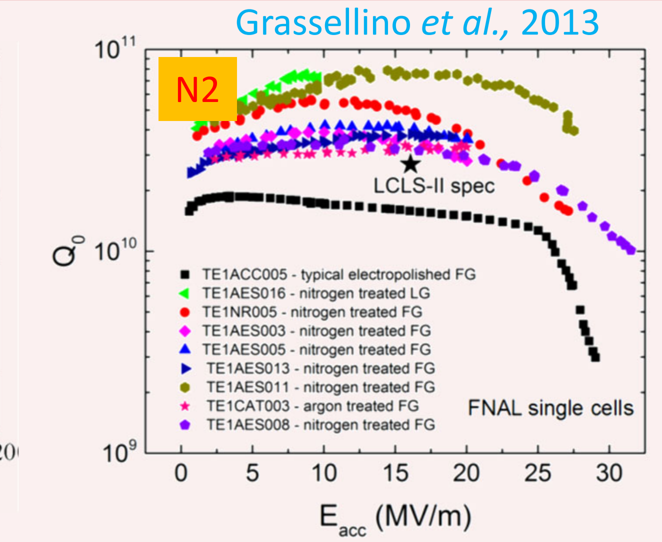

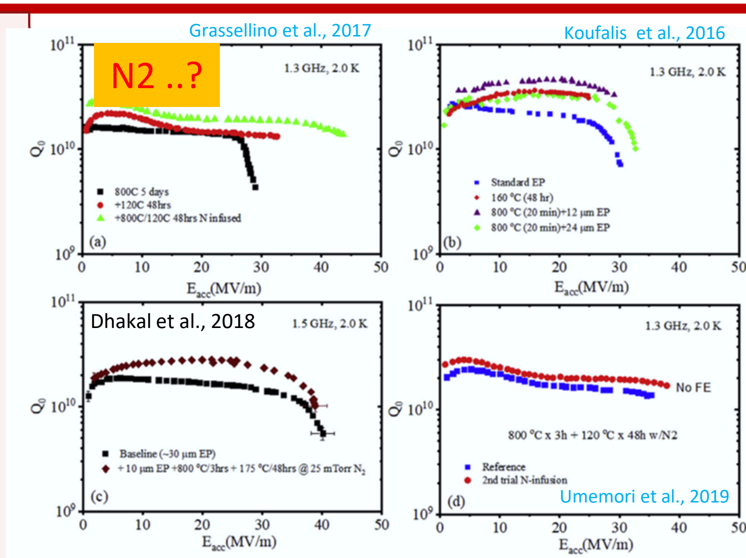

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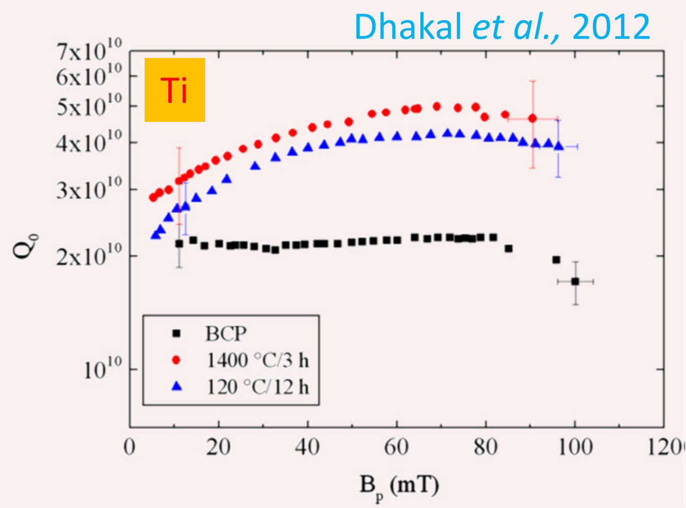

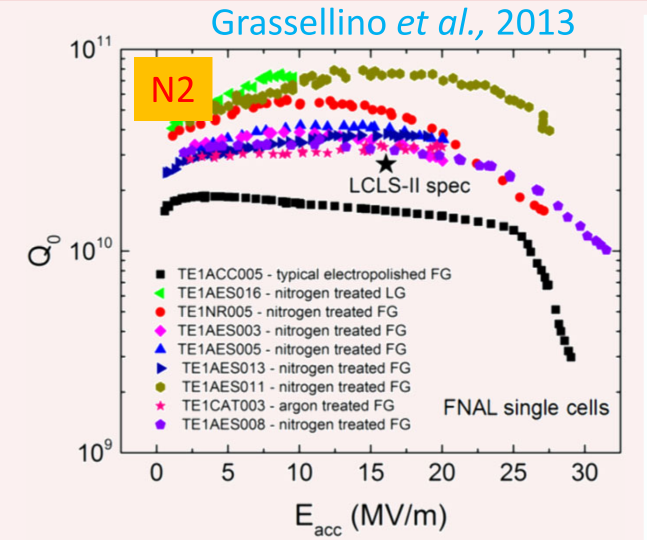

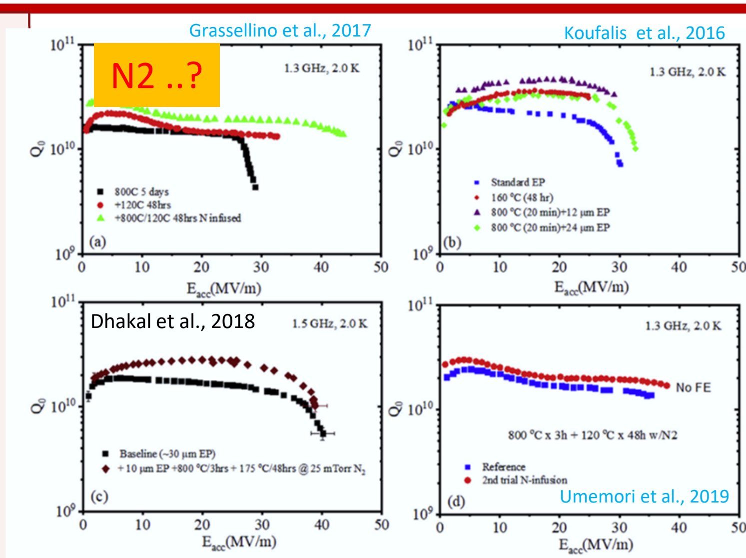

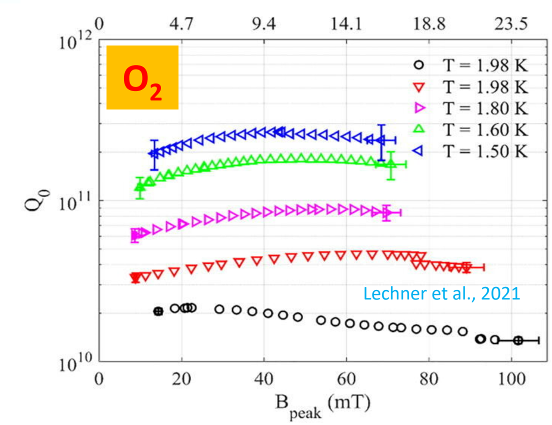

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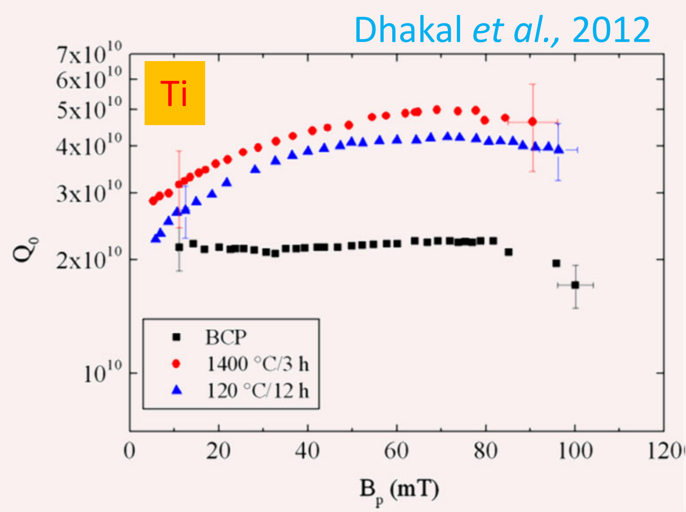
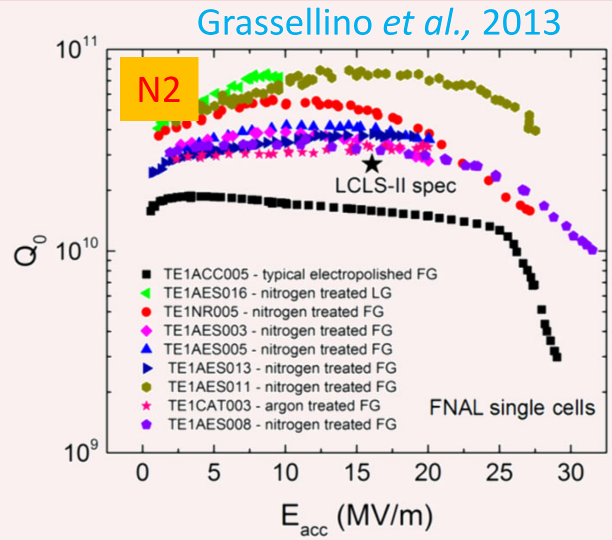
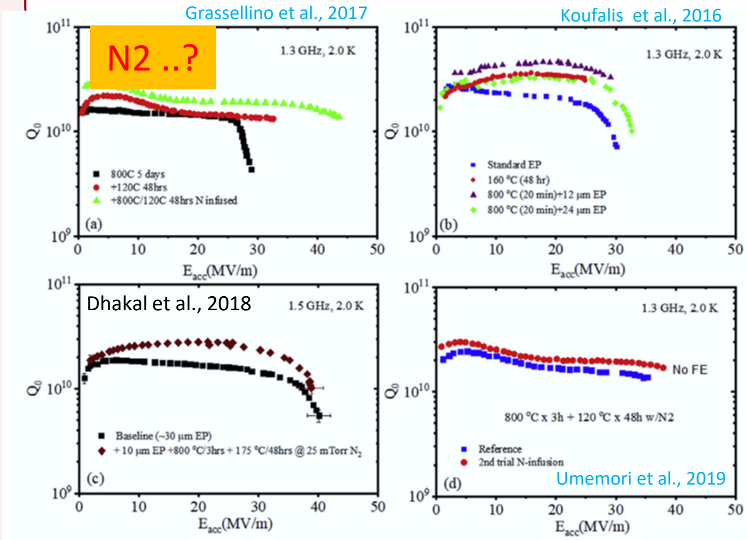
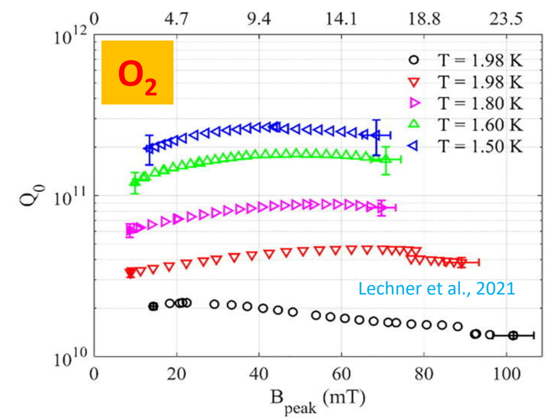






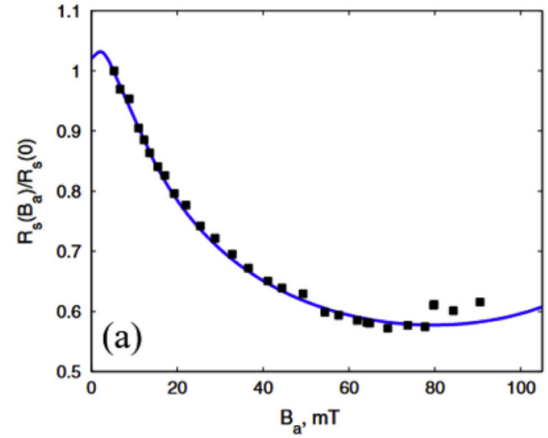


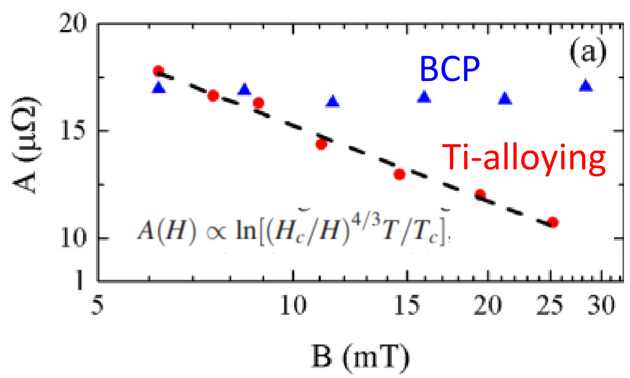
High Q_0 has been realized with surface alloying within the rf penetration depth with

- Titanium
- Nitrogen (Doping/infusion)
- Oxygen (Mid-T bake)
- ……

High Q_0

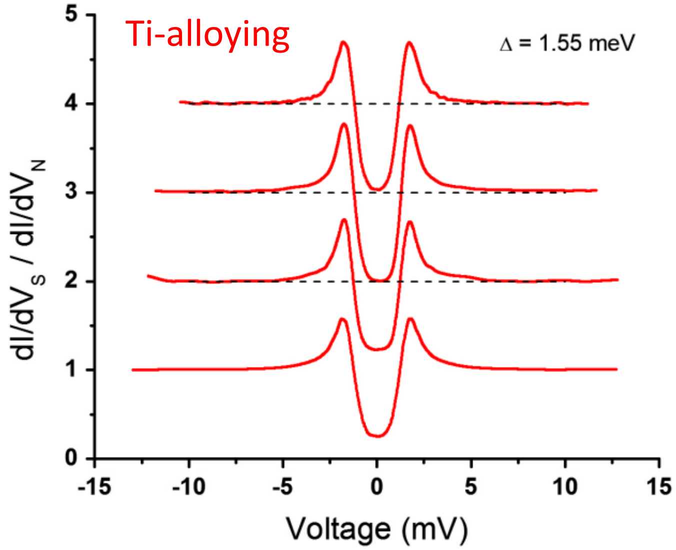
- The quality factor increases with the increase in accelerating gradient.
- The high quality factor was the result of reduction in BCS surface resistance (temperature dependent part of surface resistance) as a result of impurity.
- The reduced dissipation was explained due to the current-induced broadening of the quasiparticle density of states in dirty limit.
- Few other theoretical models were proposed to explain the Q-rise phenomenon.

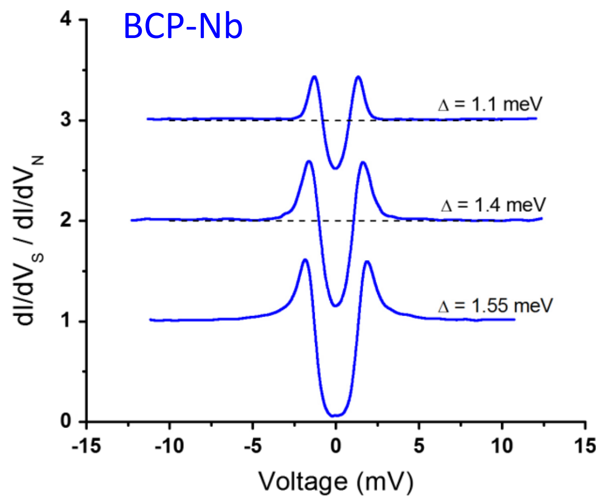


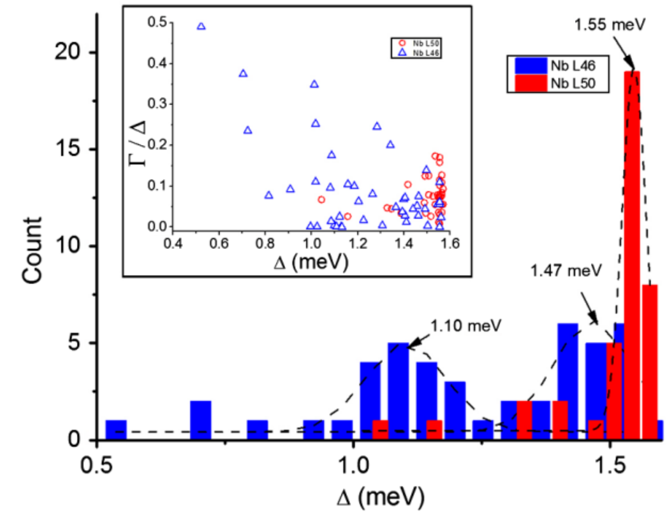


Gurevich , PRL 2014
Ciovati et al., APL 2014

Q-rise and DOS with PTC





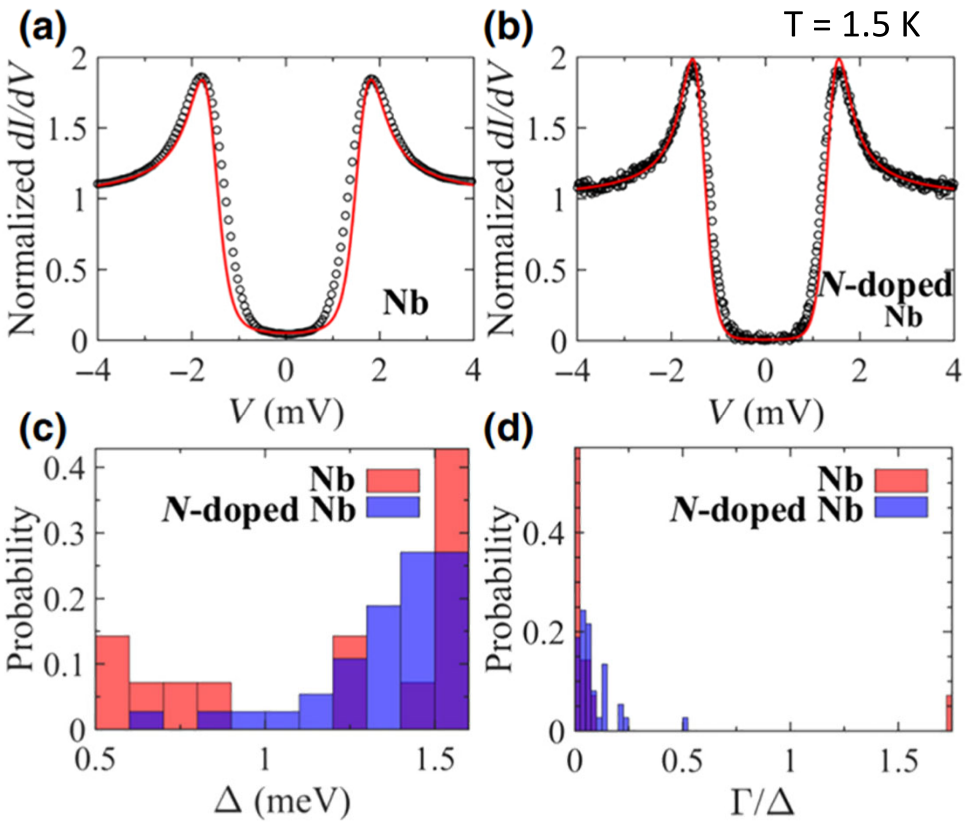


- Single gap sharply peaked at 1. 55 meV with low Γ/Δ indicate the uniform surface
- Large spread in gap (1.1 – 1.47 meV), indicative of non uniform superconducting properties

Treatment improved significantly the surface superconductivity in terms of the amplitude of the gap and the pair-breaking parameter, as well as their uniformity, are consistent with the improvement of the cavity Q_0 value

P. DHAKAL et al. Phys. Rev. ST Accel. Beams 16, 042001 (2013)

Q-rise and DOS with STM

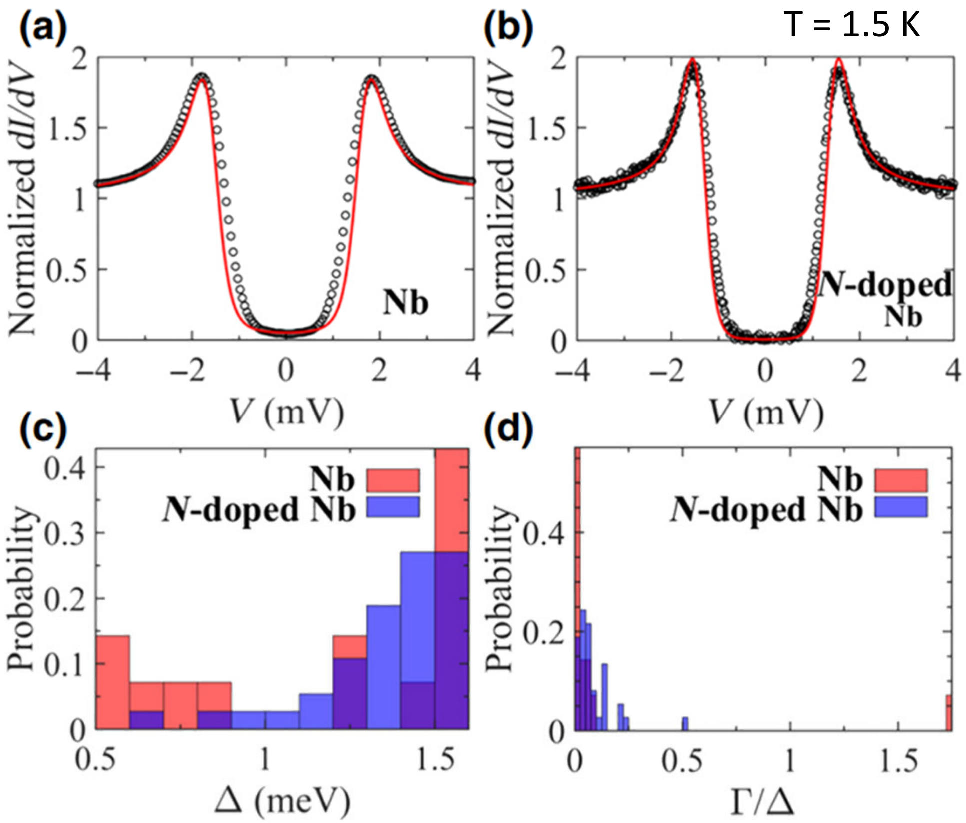


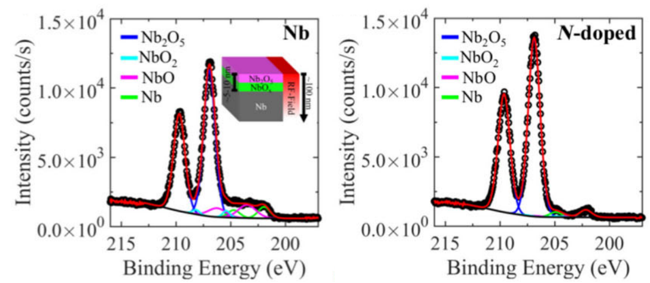
Stronger inhomogeneities of superconducting properties on non doped Nb

E. Lechner et al. Phys. Rev. Applied, 13, 044044 (2020)

Q-rise and DOS with STM

T = 1.5 K





Sample	Nb	*N*-doped
Nb_2O_5 (%)	80.1	94.8
NbO_2 (%)	6.4	4.0
NbO (%)	11.2	0.7
Nb (%)	2.3	0.5

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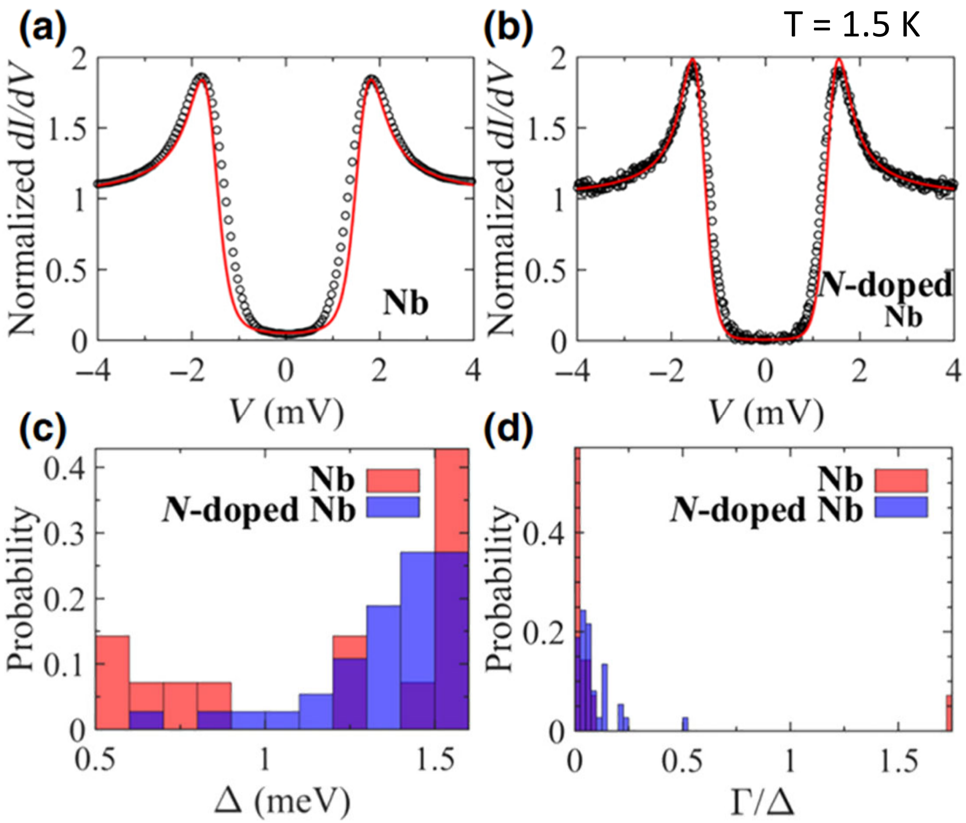

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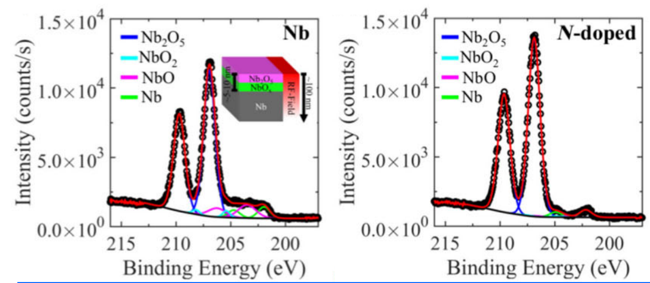

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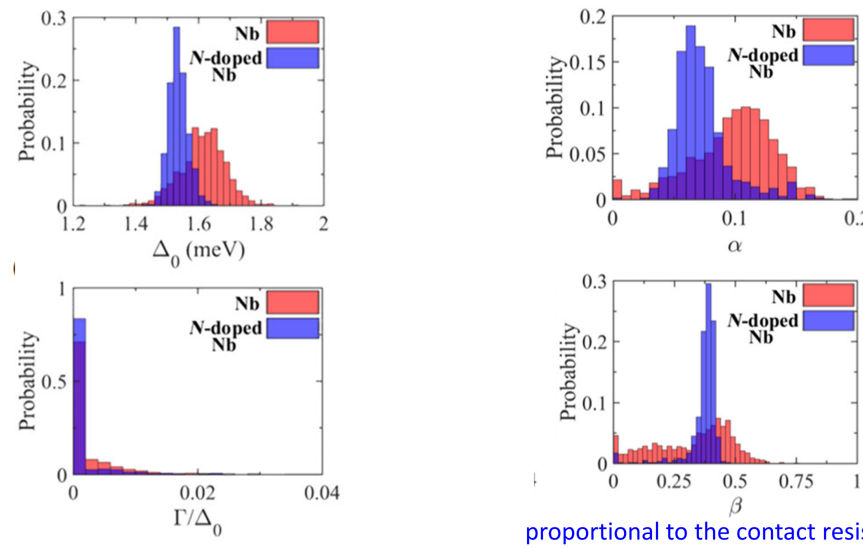
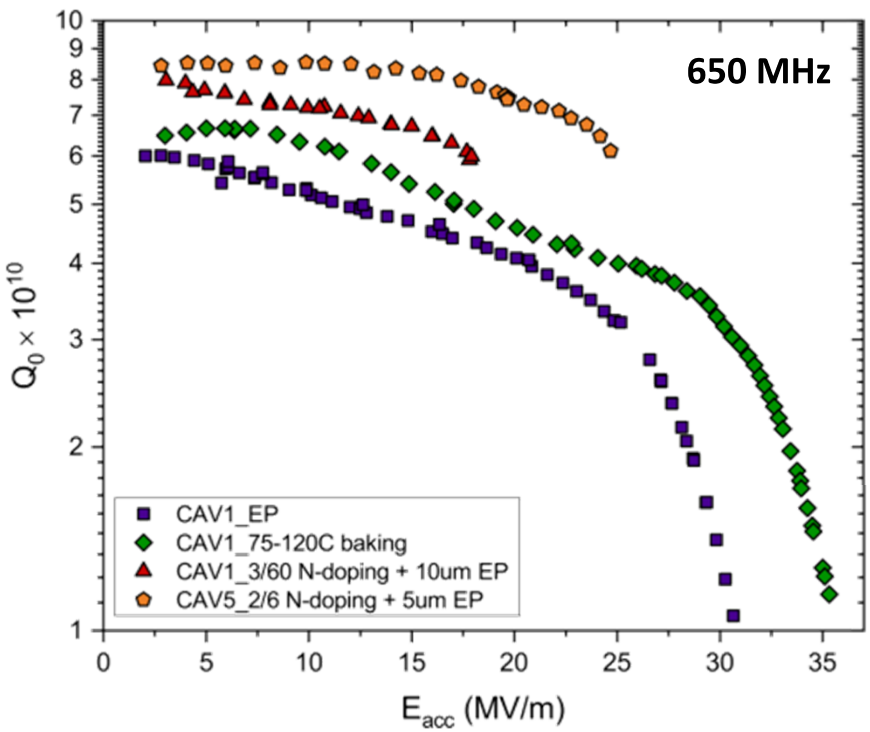
thickness of the normal sub-oxide layer



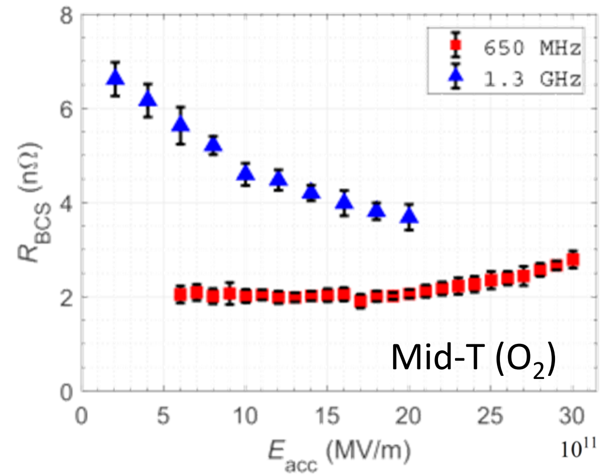
proportional to the contact resistance

E. Lechner et al. Phys. Rev. Applied, 13, 044044 (2020)

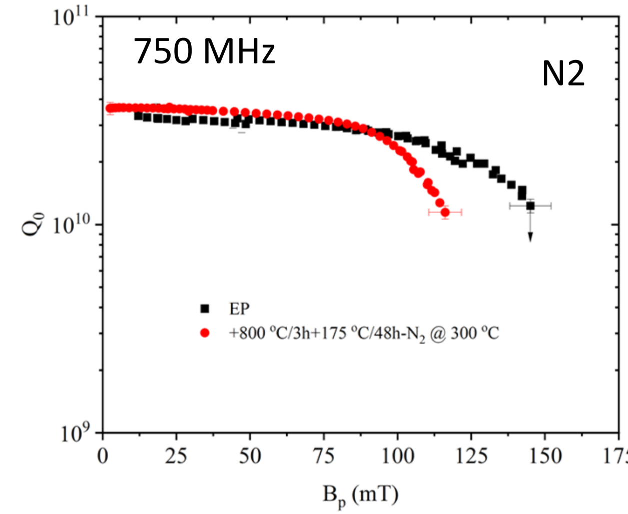
Do we always get Q-rise with alloying?



Martinello et al., J. Appl. Phys. 130, 174501 (2021)



Sha et a., Appl. Sci. 2022, 12, 546



Benefit was observed on overall Q_0 with absence of Q-rise

Do we need impurity alloying for Q-rise?

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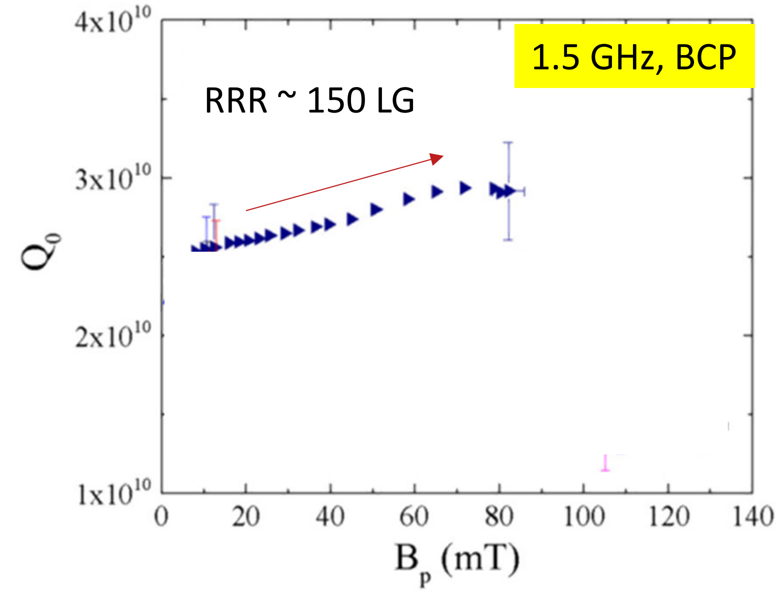

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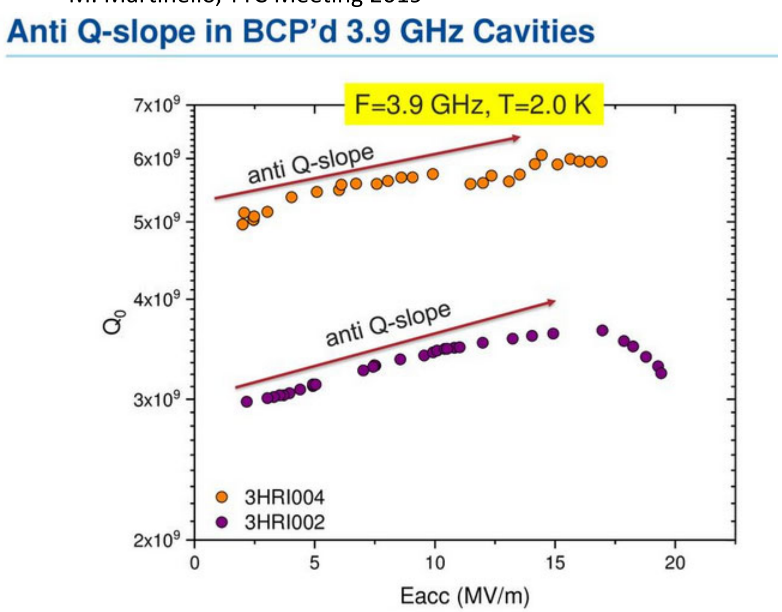
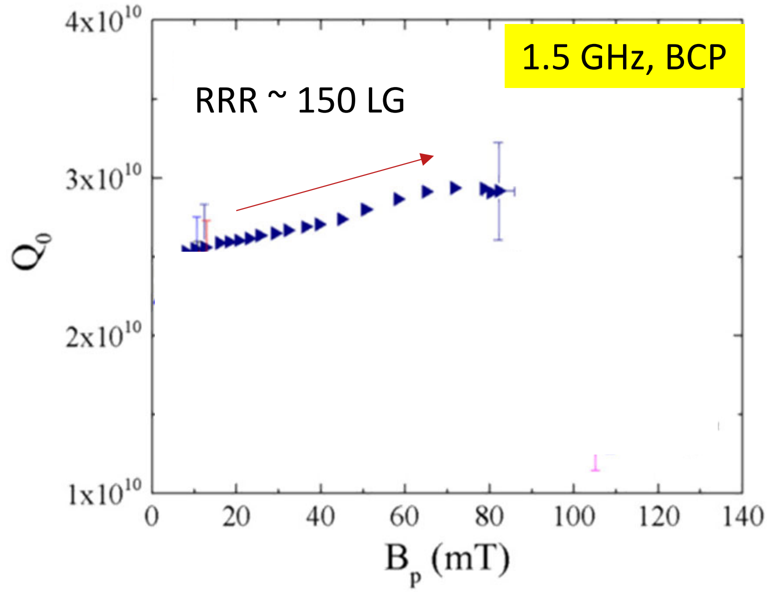
M. Martinello, TTC Meeting 2019





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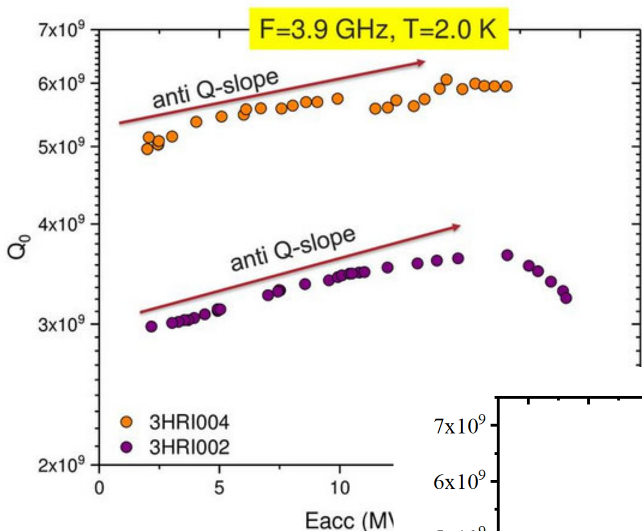
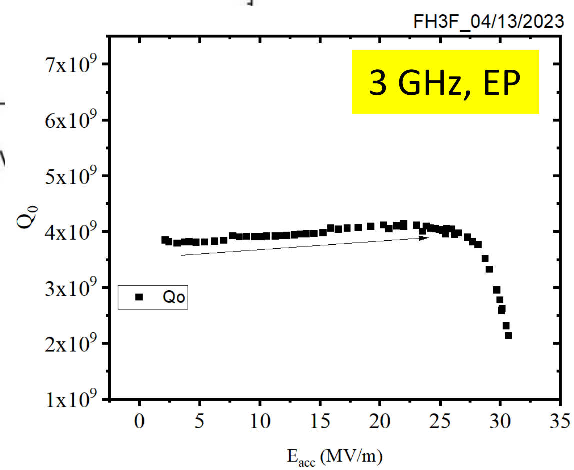
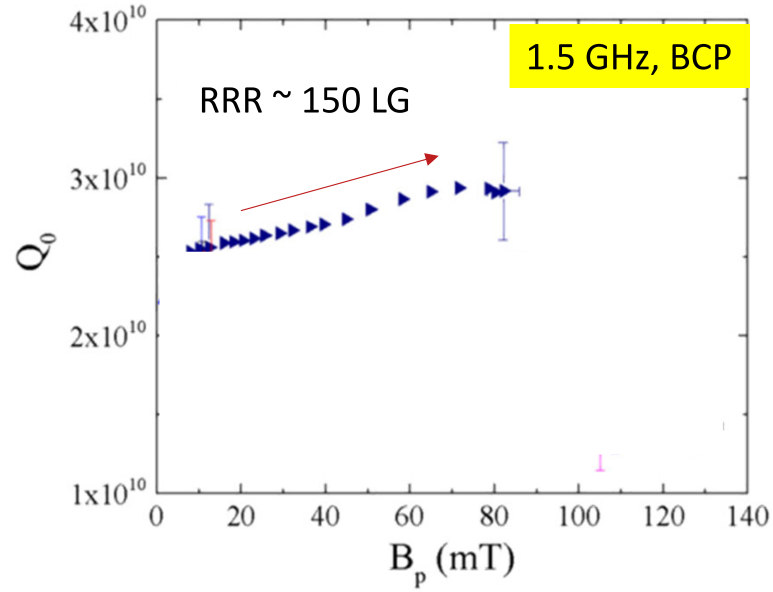
Anti Q-slope in BCP'd 3.9 GHz Cavities







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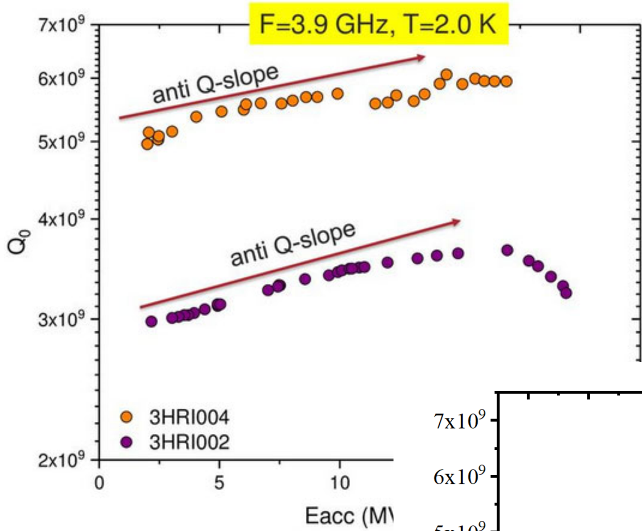

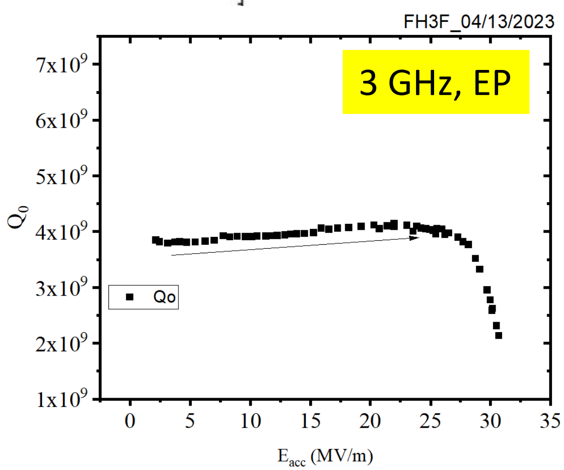

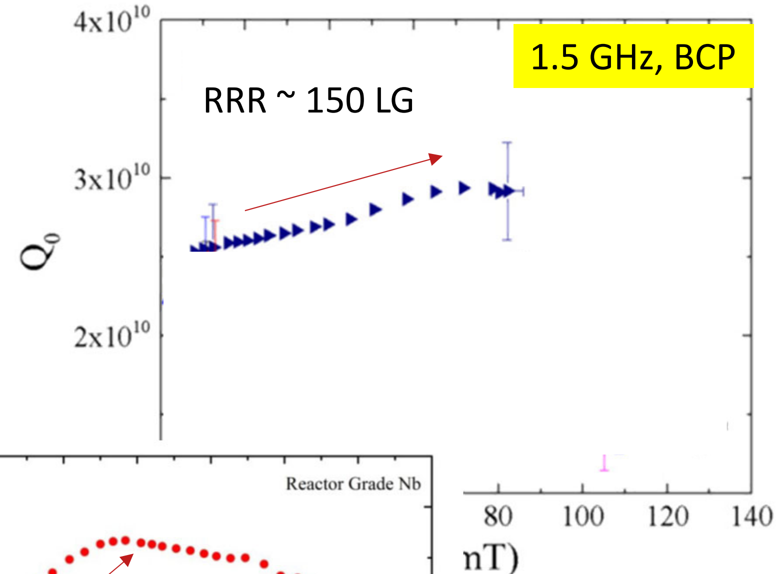

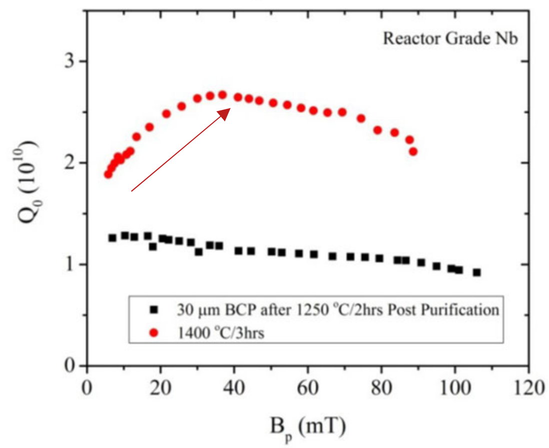

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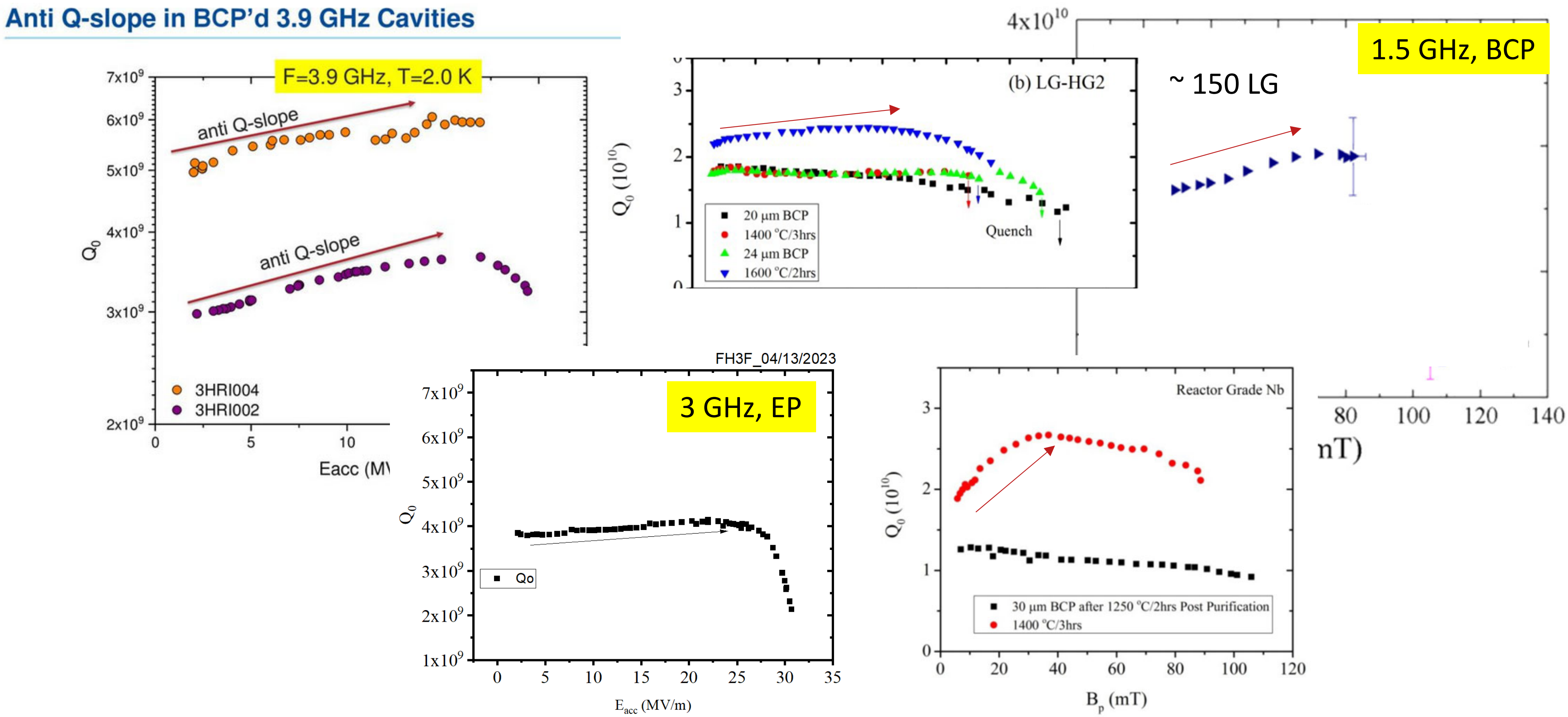

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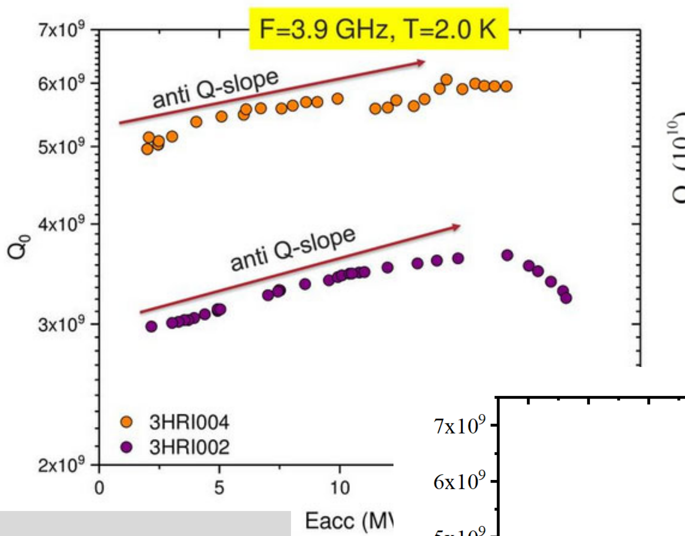
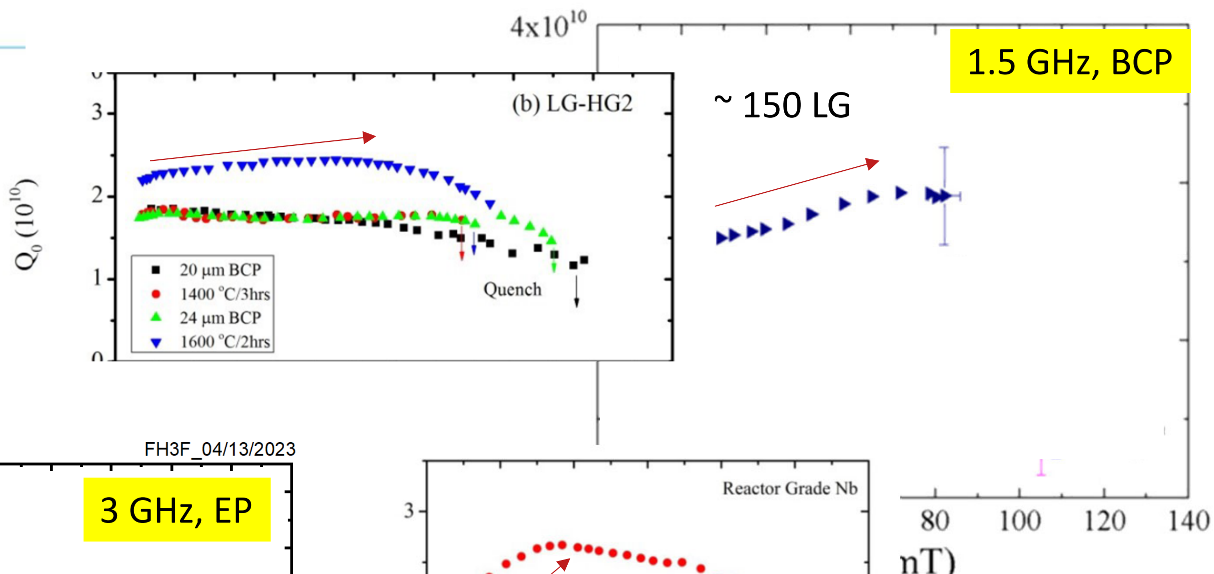
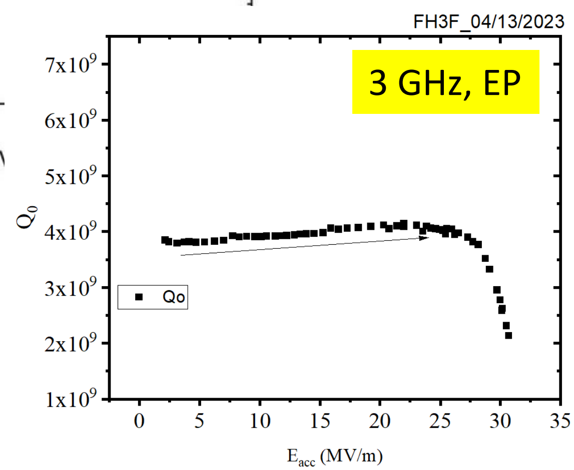
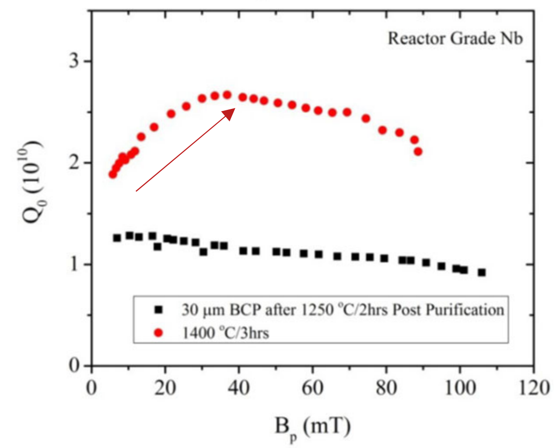




- Frequency
- Grain
- RRR
- Surface Processing (EP/BCP)

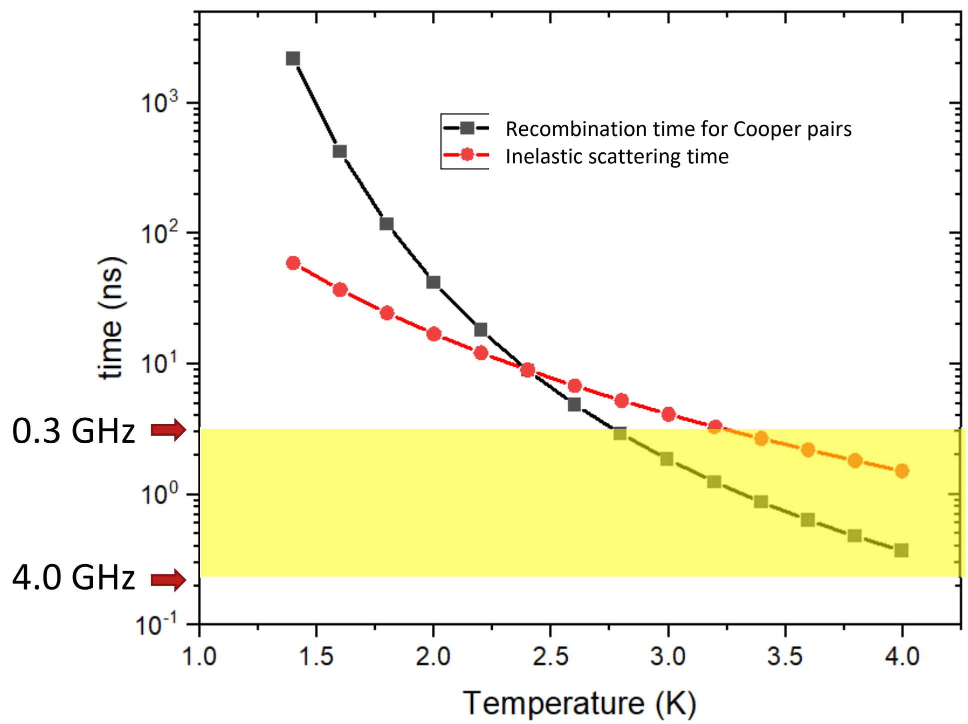




When do we get Q-rise?

τ_r = recombination time for Cooper pairs

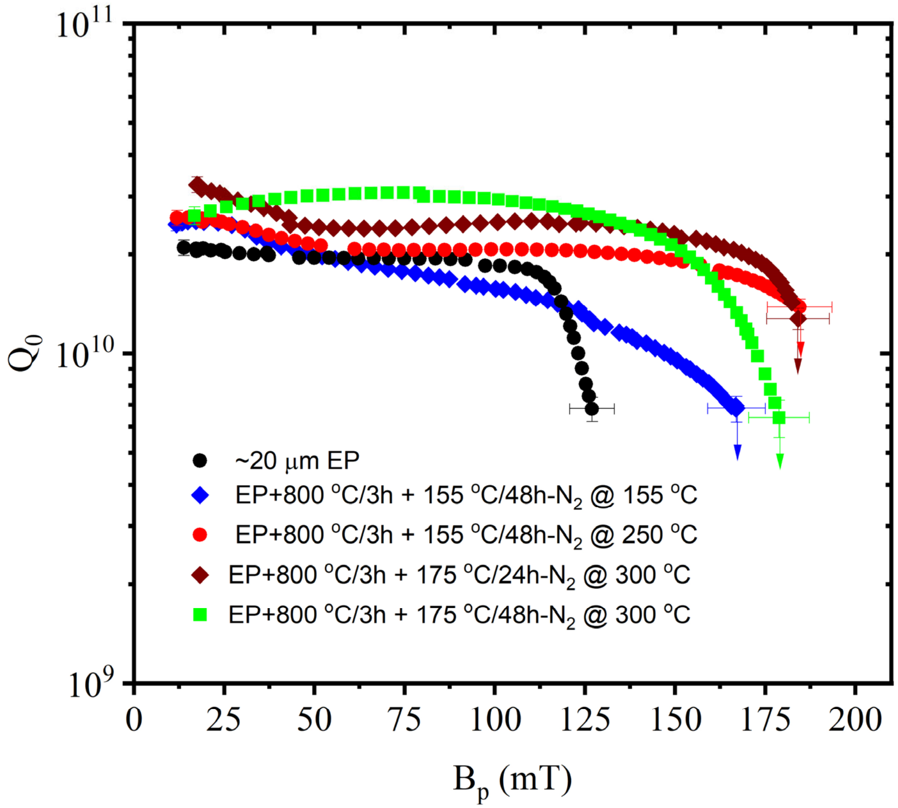
τ_s = inelastic scattering (scattering of quasiparticles on phonons)

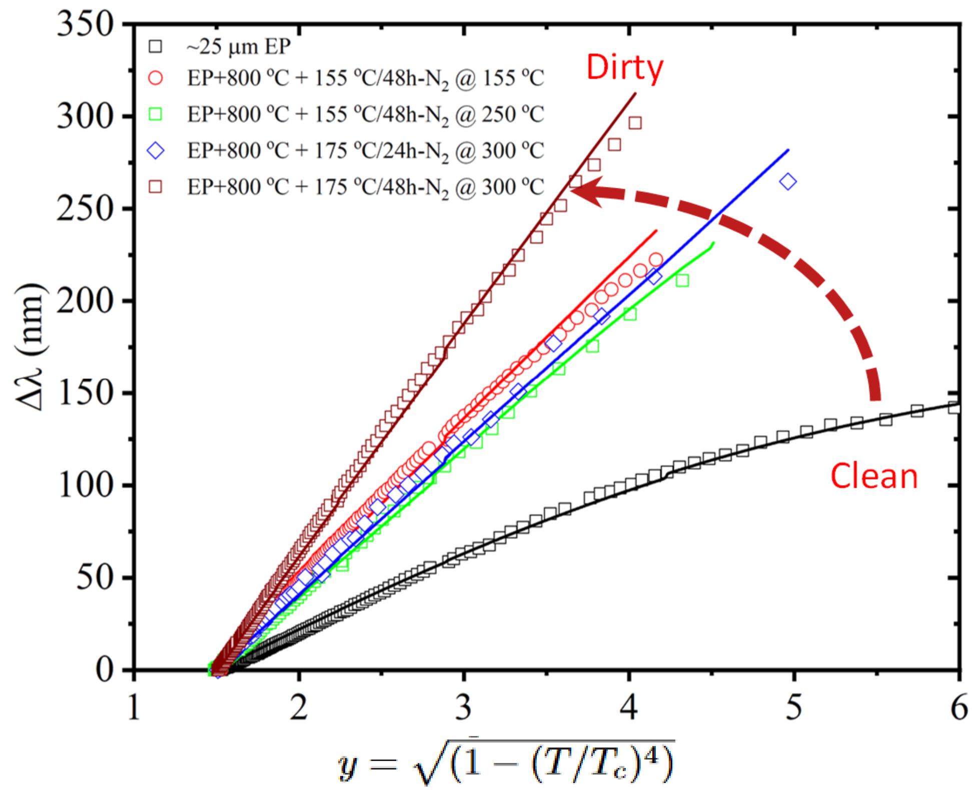


- Non-equilibrium effect occurs when (τ_s , $\tau_r > \tau_{rf}$
- Non-equilibrium effects become more pronounced at T <<T_c.
- Impurity or thin proximity coupled metallic sub oxide reduces τ_r and τ_s such that cavity drive to non-equilibrium state. Actual frequency and temperature dependence of τ_r and τ_s is very sensitive to surface state.
- For low frequency, the condition for τ_s , $\tau_r > \tau_{rf}$ may met at much lower temperature.

Gurevich, SUST (2023)
Kubo & Gurevich, PRB 100, 064522 (2019)
Kaplan et al., PRB 14, 4854 (1976)

Focus with Nitrogen treatment at Low temperature





Quality factor can be tuned with temperature and time of baking duration. The mfp can extracted from the change in penetration depth (∞ Δf), resulting in clean-to-dirty limit transition.

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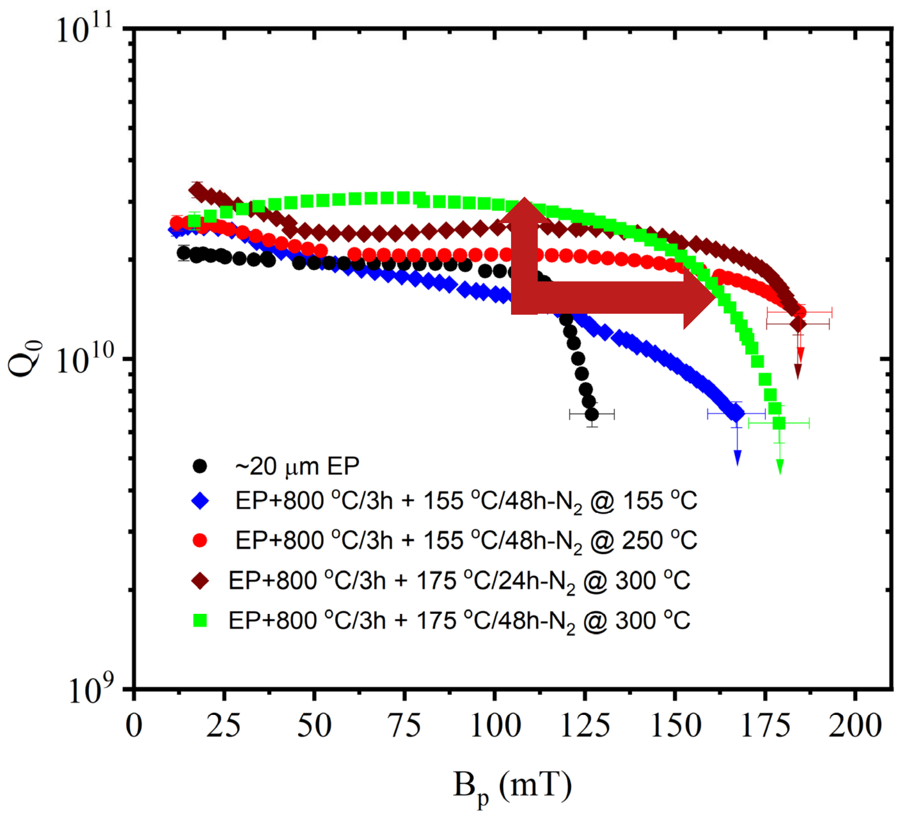

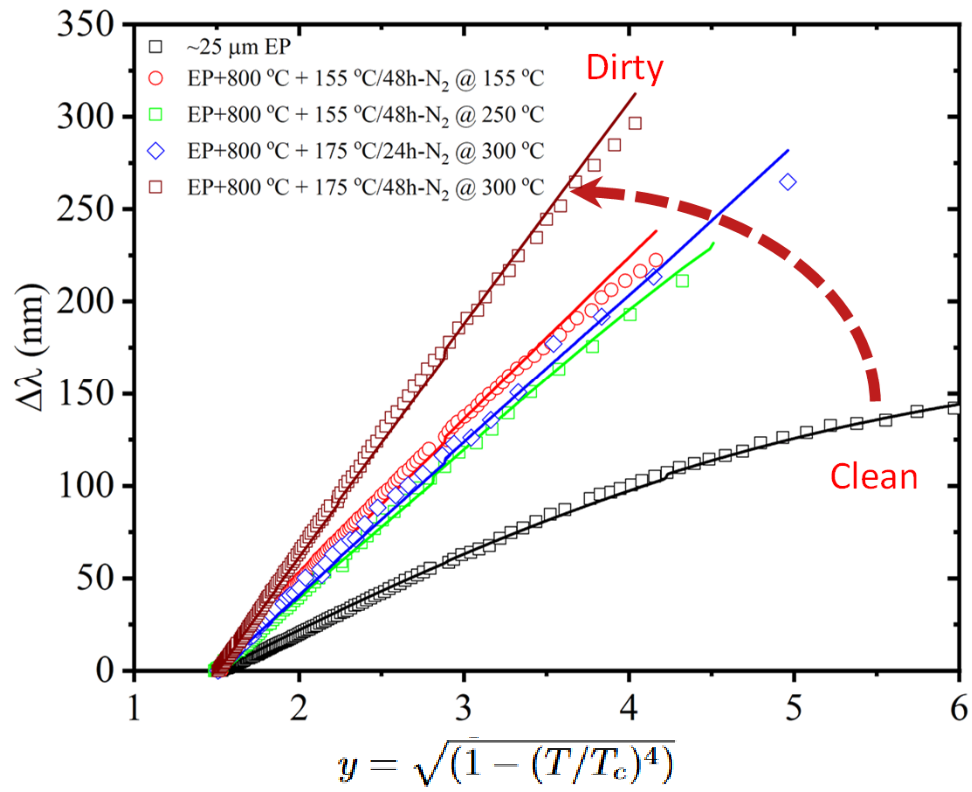

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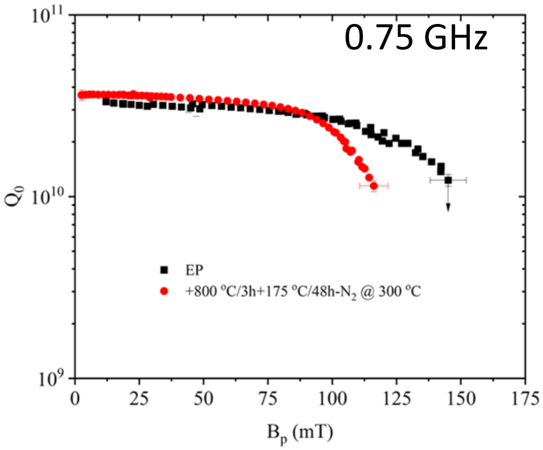
Frequency Dependence



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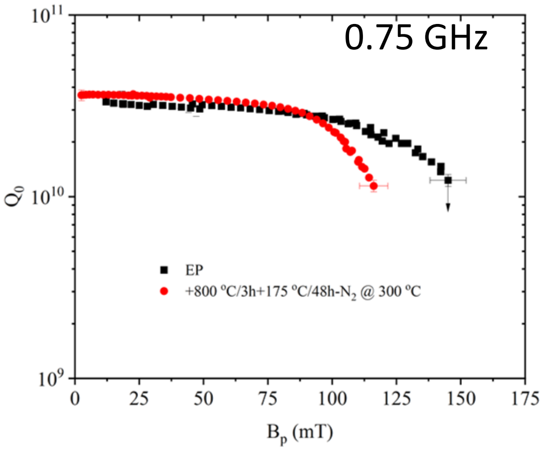

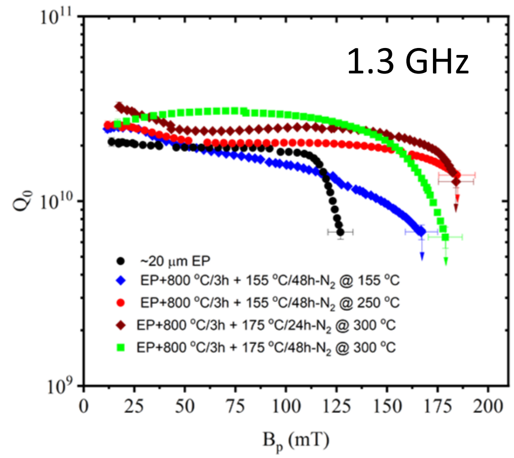

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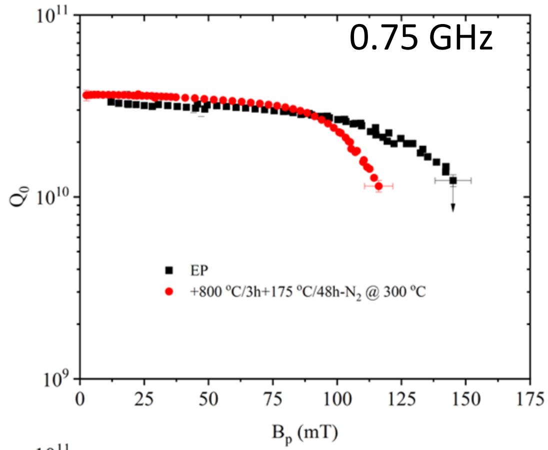

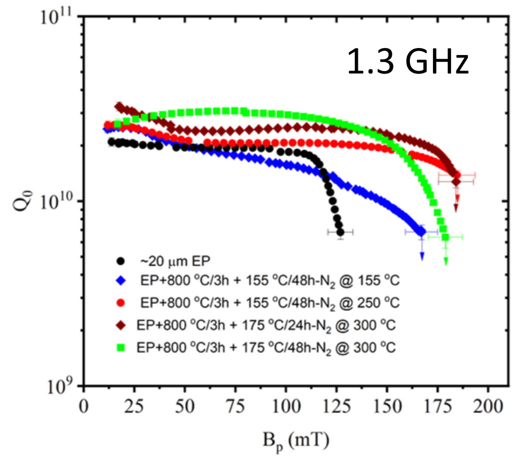

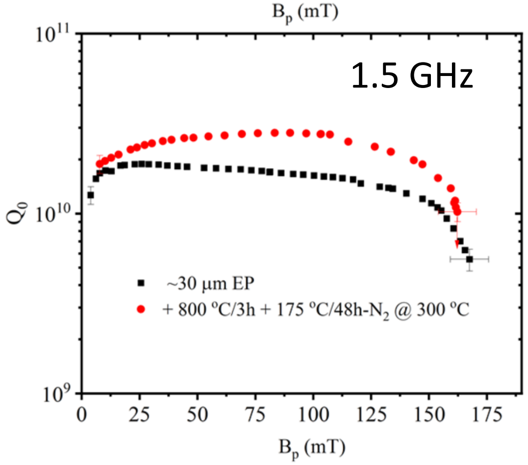

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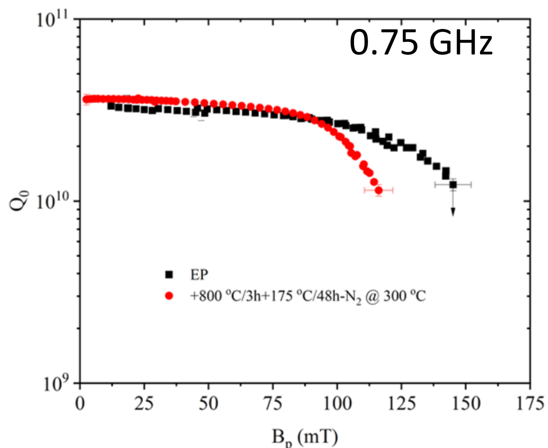
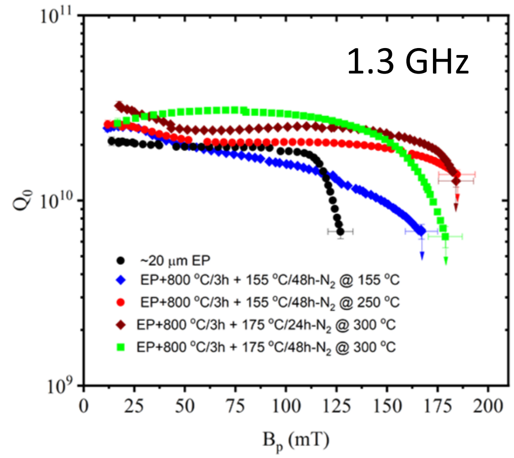
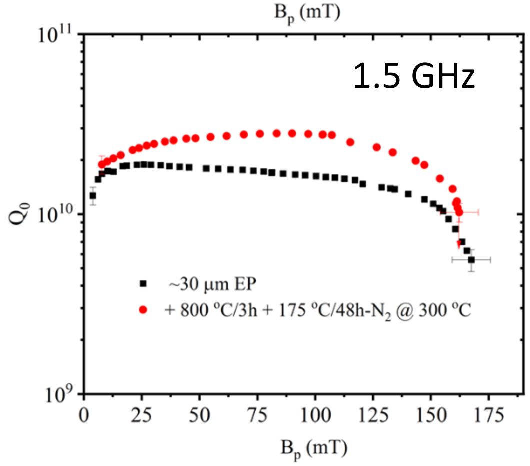
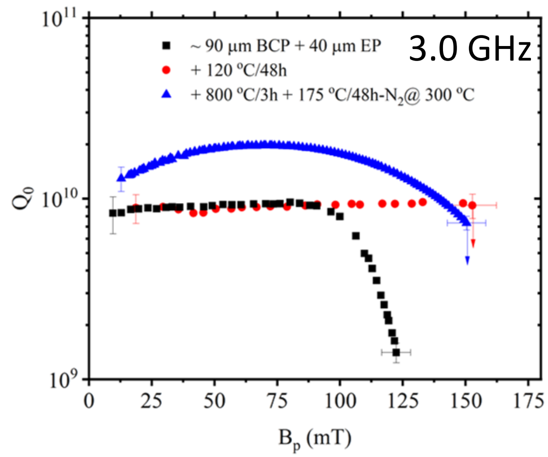
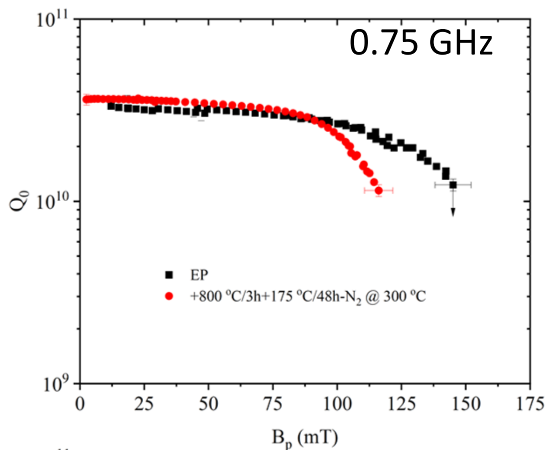


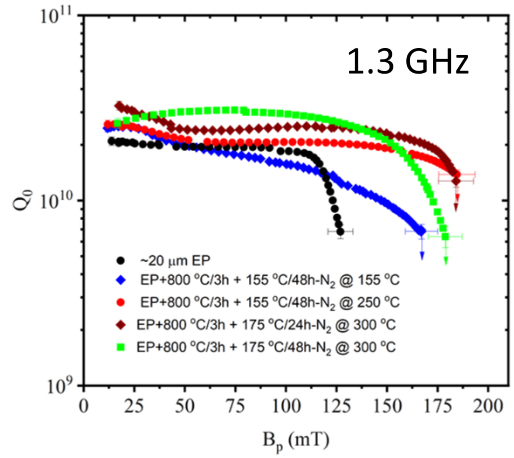


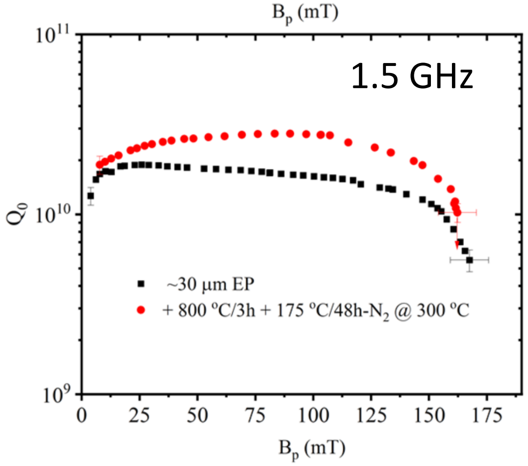


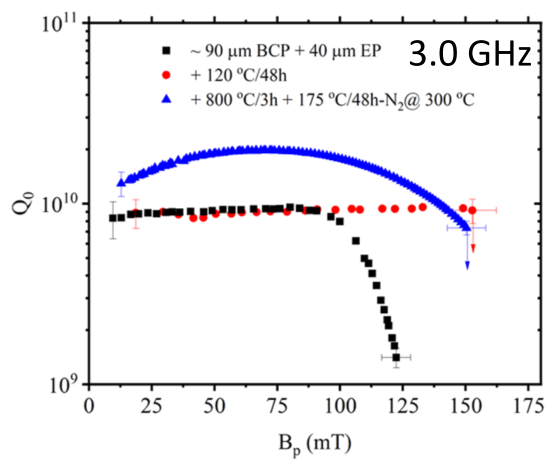


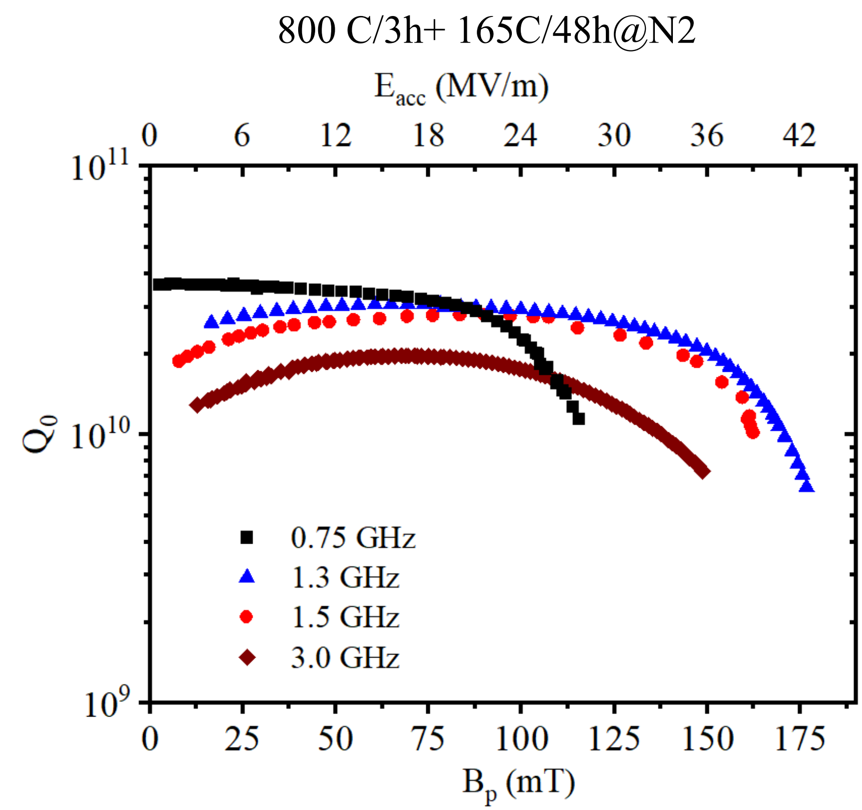
Frequency Dependence



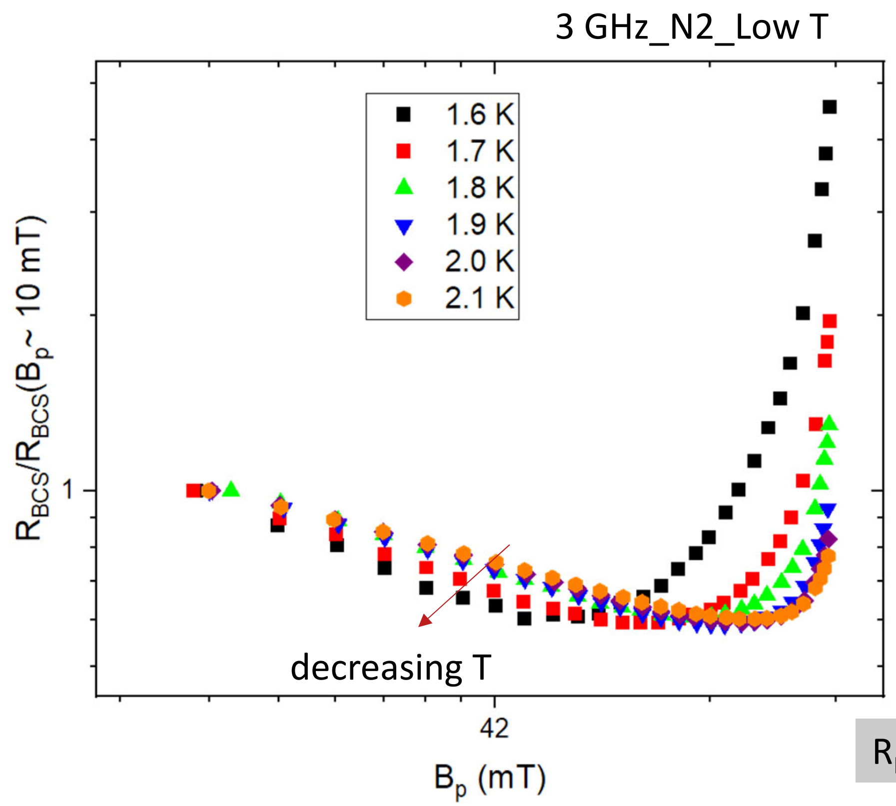


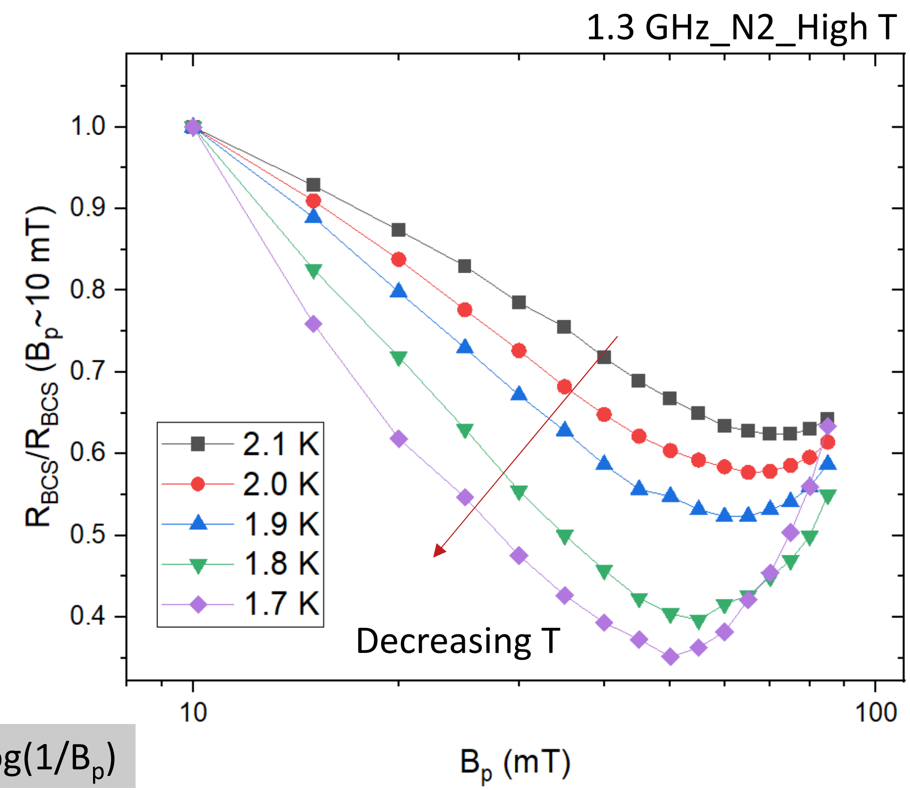






Frequency Dependence RBCS (Temperature Dependence)

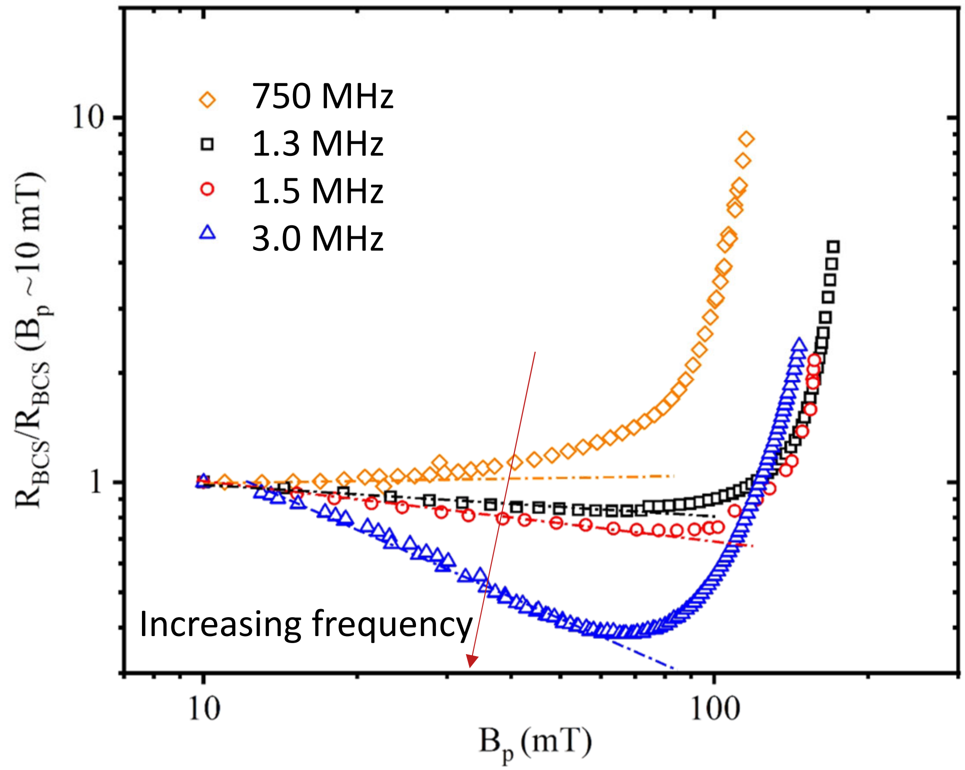




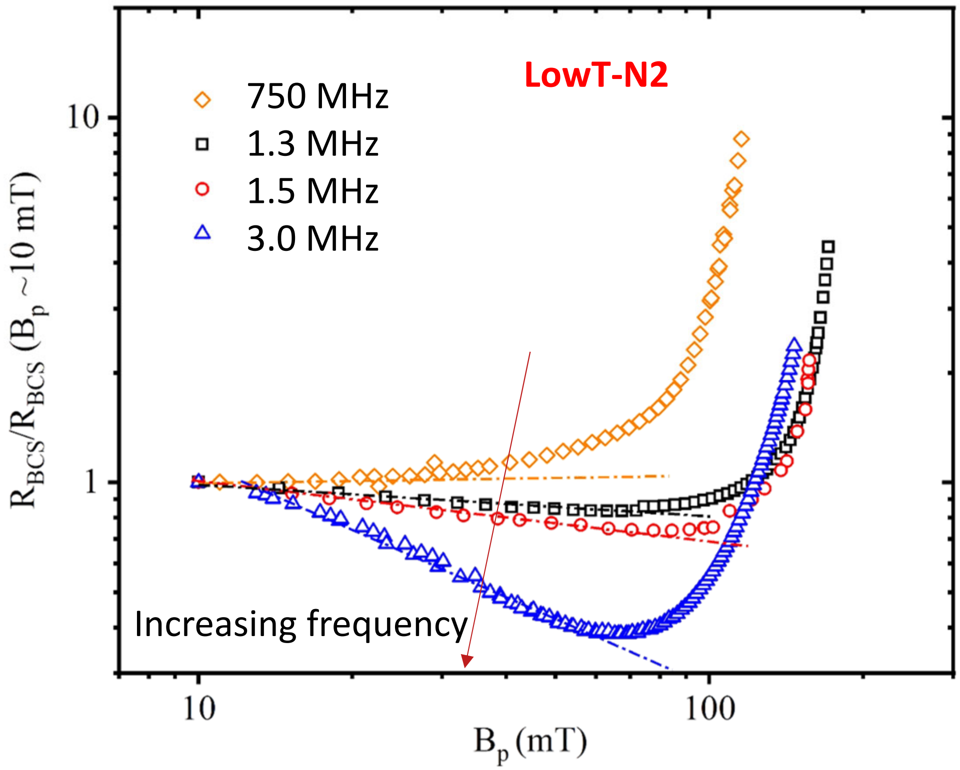
$R_{BCS} \propto Log(1/B_p)$

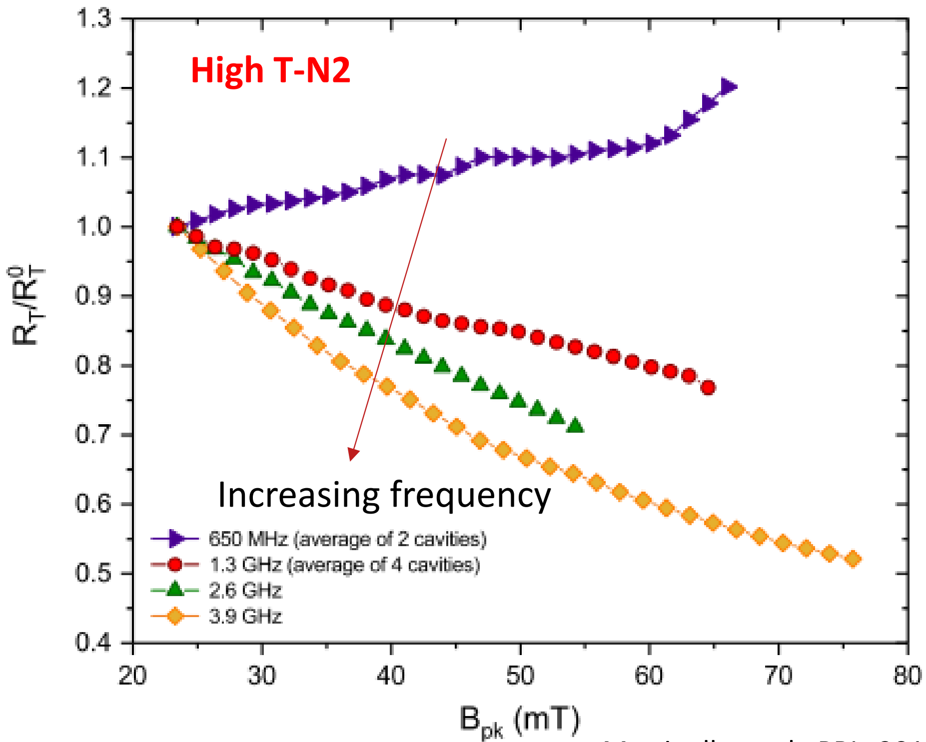
The dip in RBCS shifts to lower Bp with decreasing T, non-equilibrium effects increase with decrease in T

Frequency Dependence R_{BCS}



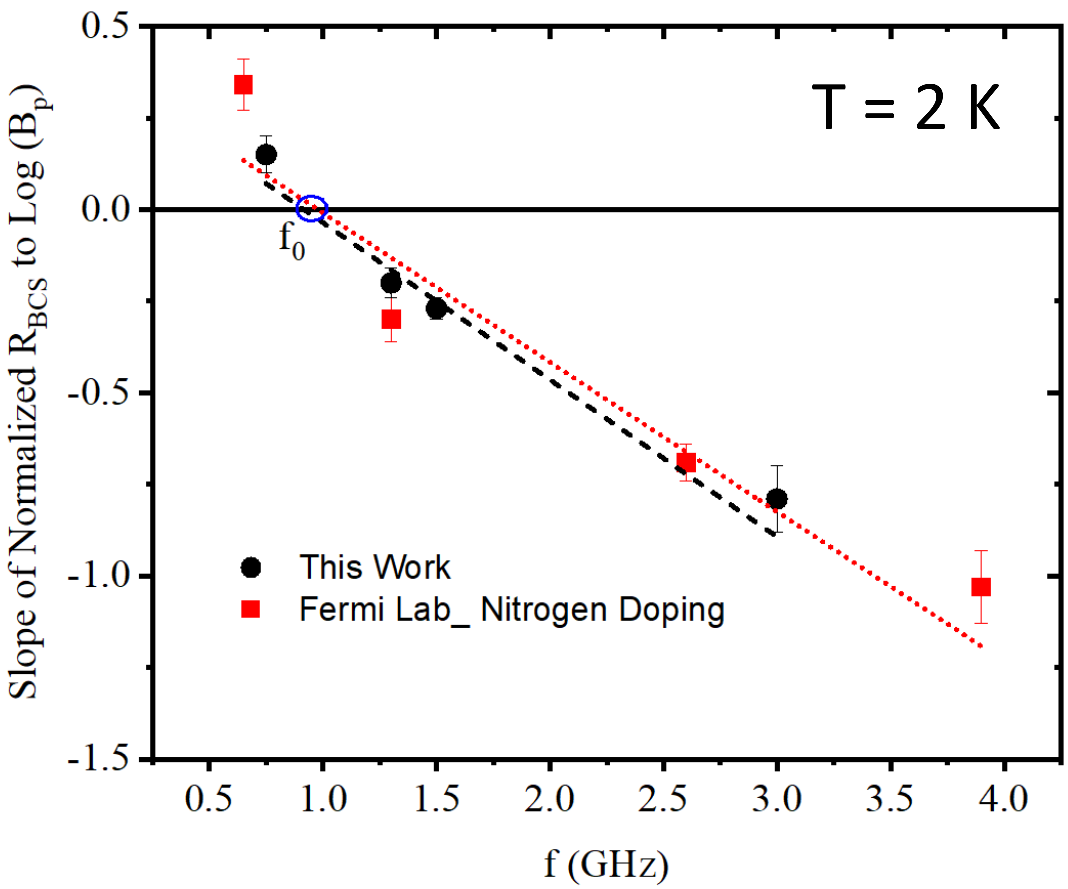
Frequency Dependence R_{BCS}





Martinello et al., PRL, 2018

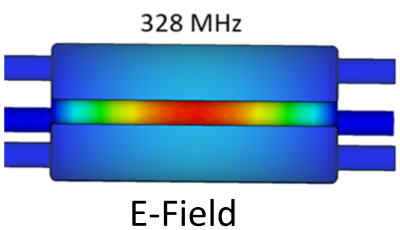
Requirement for Q-rise (frequency)

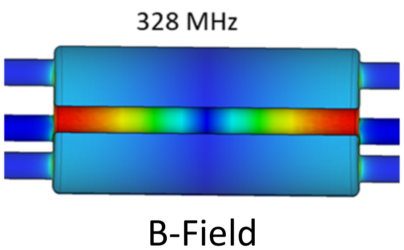


- Q-rise phenomenon observed on cavities resonating frequency higher than 900 MHz at 2.0 K
- The non equilibrium effects may appear at frequency higher than threshold frequency (~ 0.9 GHz) at 2.0 K
- At low frequency, the non-equilibrium effect is negligible, but it may play a role at much lower temperature.

Kubo & Gurevich, PRB, 2019

Half Wave Coax (Recent Results)

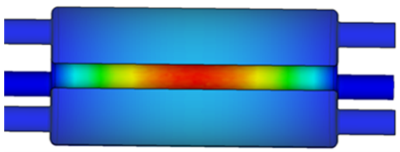




- Half wave coaxial cavity with first 4 TEM modes.
- Baseline measurements with BCP, $R_s(T)$ and $R_s(B_p)$.
- Mid-T bake with 320 C/ 100 mins. Test all 4 modes for $R_s(T)$ and $R_s(B_p)$.

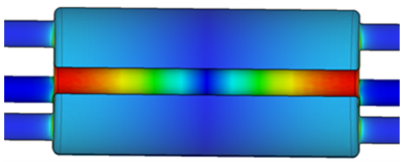
Half Wave Coax (Recent Results)

328 MHz



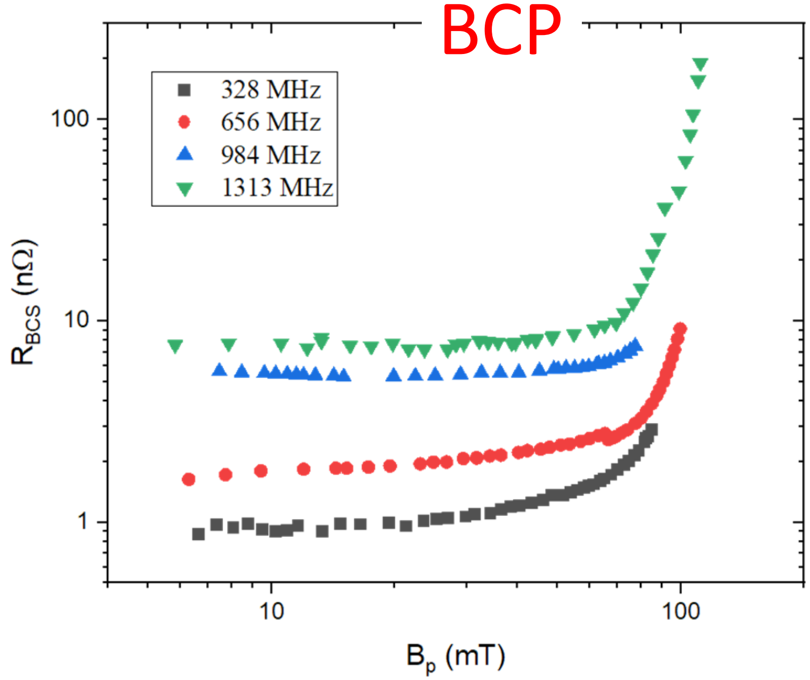
E-Field

328 MHz



B-Field

BCP



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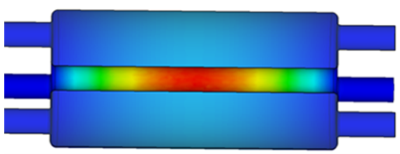
SRF 2023 GRAND RAPIDS Jefferson Lab

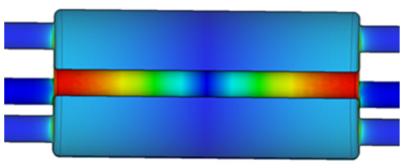
Half Wave Coax (Recent Results)

328 MHz

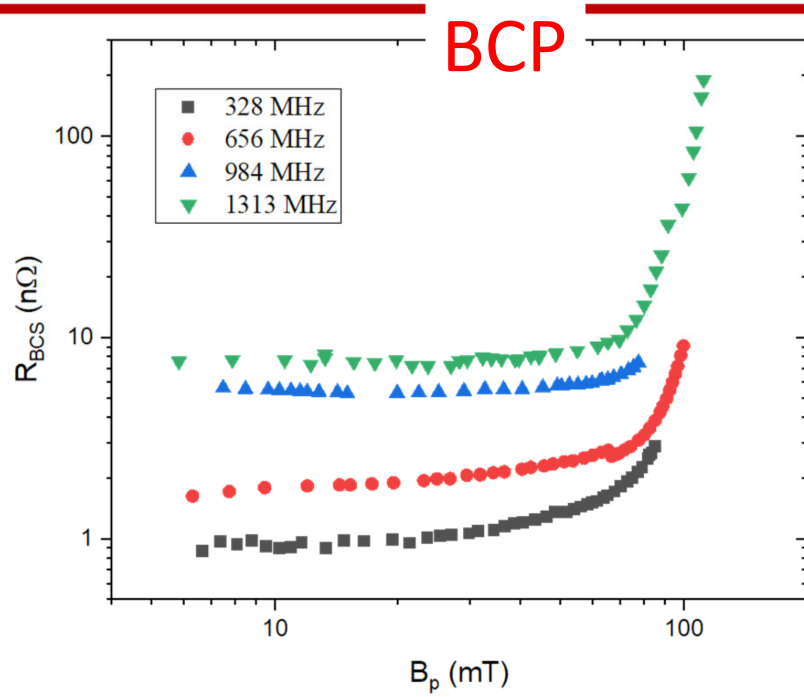


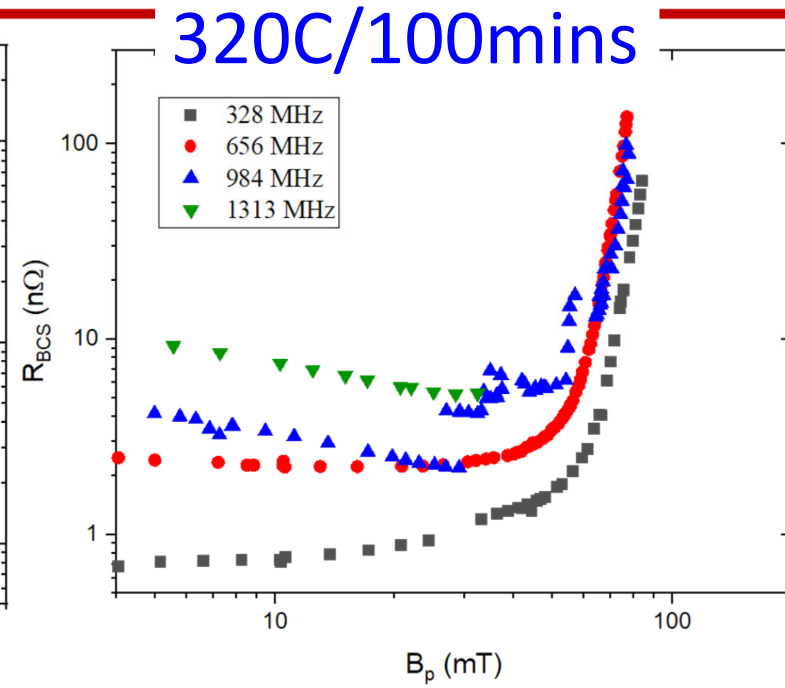
E-Field

328 MHz



B-Field





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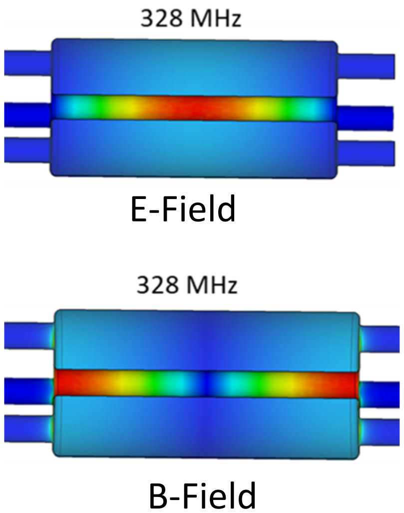

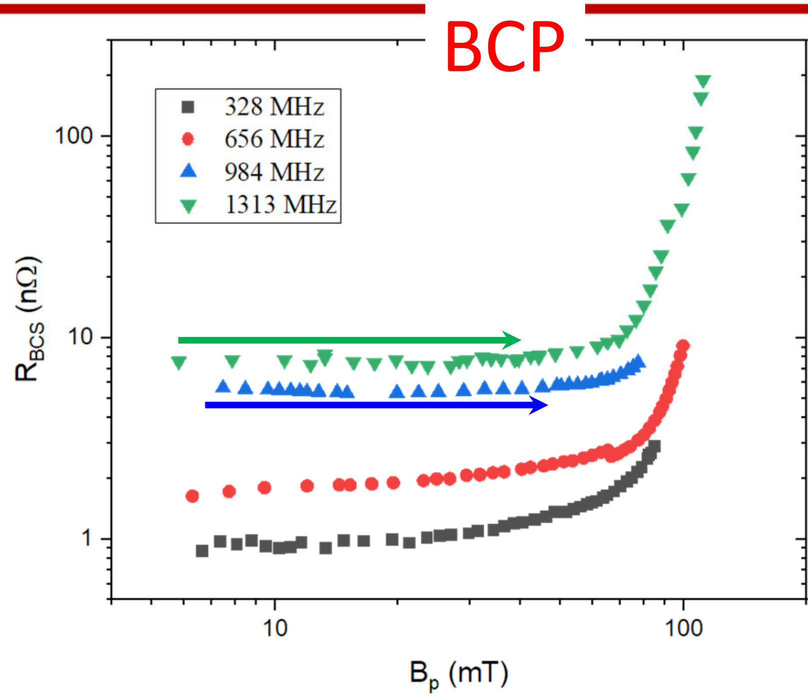

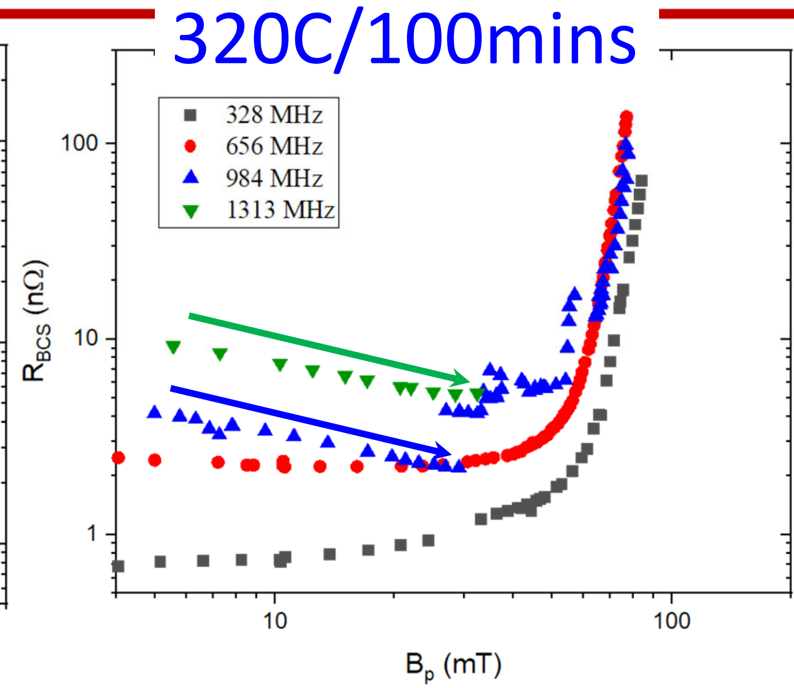

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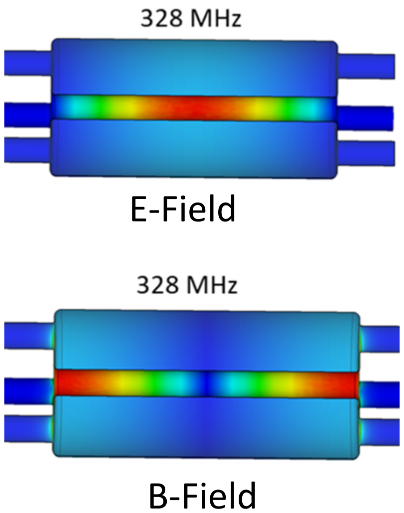

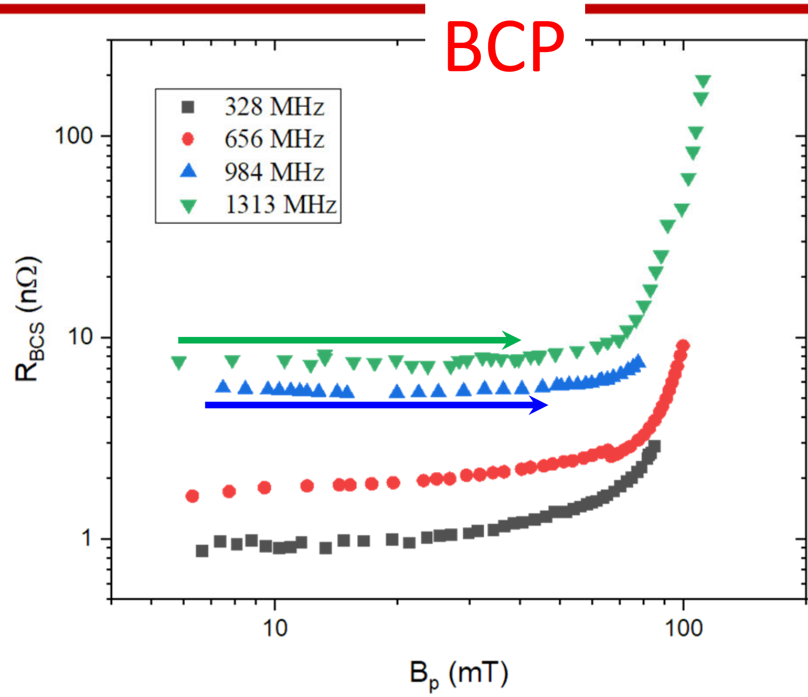

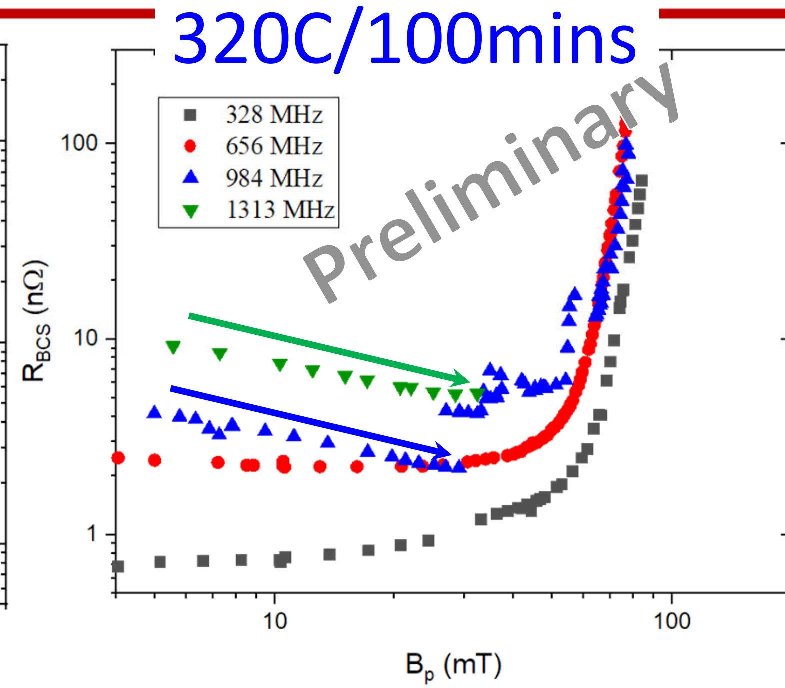

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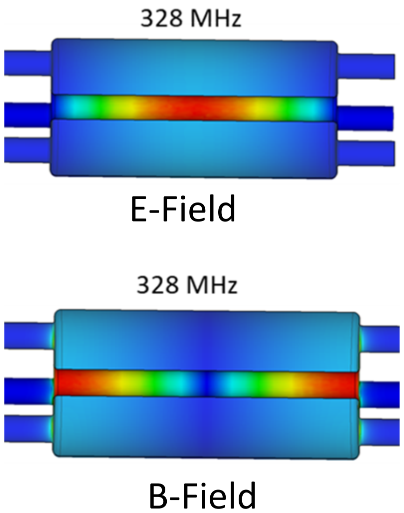

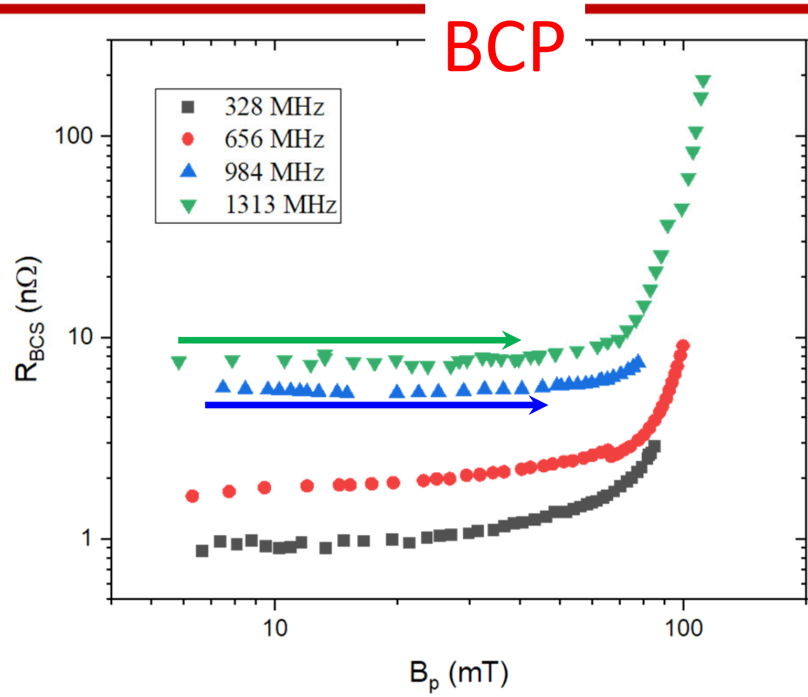

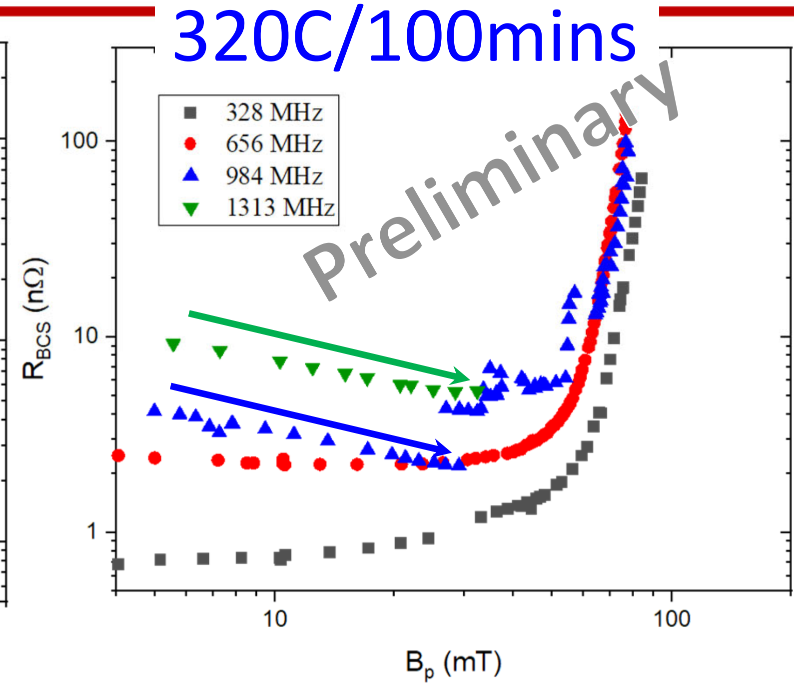

WEPWB052
N. Raut et al.

- Half wave coaxial cavity with first 4 TEM modes.
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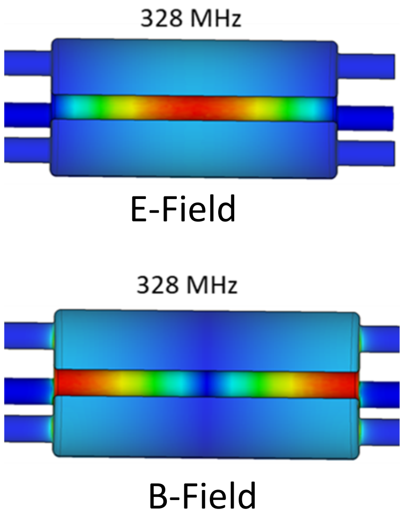
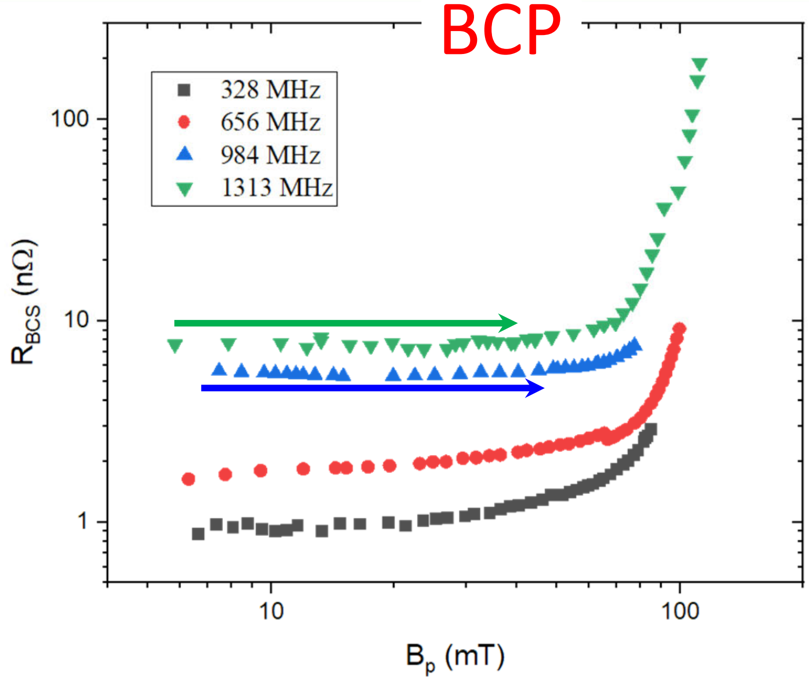
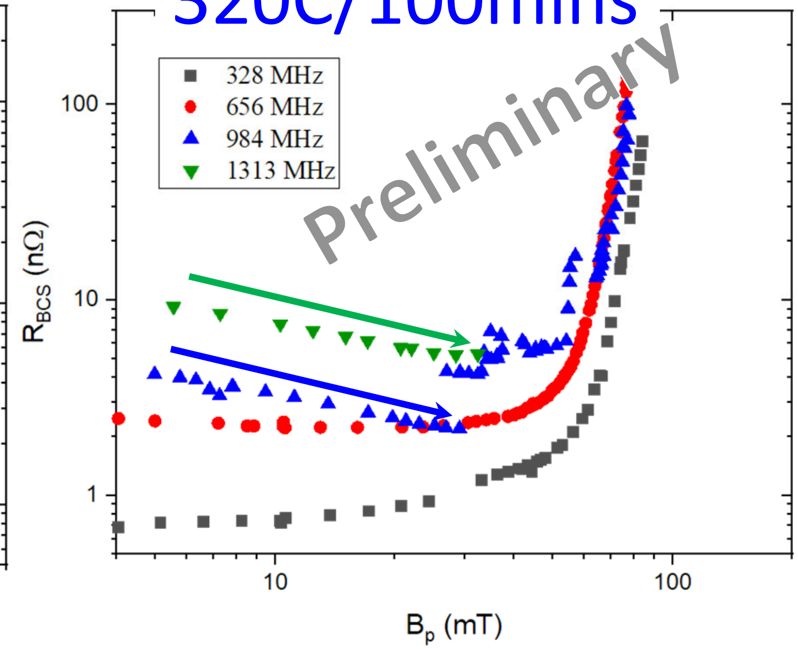
Half Wave Coax (Recent Results)







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WEPWB052
N. Raut et al.

Kolb et al., arXiv:2306.12588

Summary and Outlook

- Improvement in the quality factor of SRF Nb cavities was observed after annealing at 800 ^{o}C/3 h in vacuum followed by baking at 120 - 175 ^{o}C in low partial pressure of nitrogen inside a furnace compared to the traditional 120 ^{o}C bake in UHV.

- Higher accelerating gradient were achieved compared to the high-T N2 treatment.

- Q-rise phenomenon observed on cavities resonating frequency higher than 900 MHz based on available RF results at 2.0 K.

- The crossover frequency and temperature from equilibrium to non-equilibrium or vice versa still need to be investigated. This could be explored in multi-mode half wave resonators.

Thank you for listening!